

Late Quaternary paleohydrologic and paleotemperature change in southern Nevada

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ABSTRACT

Paleo-spring discharge activity in the southern Great Basin responded to changes in recharge, hence climate changes, in high mountain areas during the late Quaternary. In our study, we examined four stratigraphic sections in southern Nevada in order to reconstruct paleohydrologic change spanning the last two major discharge cycles. The largest discharge event in those sections is expressed as extensive wetland deposits (Unit B) that fall beyond the range of radiocarbon dating (>41 ka). We tentatively correlate this event with marine isotope stage 6, which is so conspicuously represented in cores from Death Valley and Owens Lake. Major wetlands were also present during last glacial maximum (Unit D) deposited between 16.4 and <26.3 ^{14}C ka. The absence of any dates between 16.4 and ca. 14.5 ^{14}C ka may indicate a period of relative aridity. Wetlands are also strongly expressed between ca. 13.9 and 13.5 ^{14}C ka in several sections, followed by contraction beginning between 12.9 and 12.8 ^{14}C ka. The region witnessed a modest resurgence of spring activity, expressed as black mats and spring-fed channels, starting at 11.6 ^{14}C ka, and peaking between 11 and 9.5 ^{14}C ka, followed by desiccation of most springs between 9.5 and 7 ^{14}C ka.

Detailed analysis of ostracode taxa from three stratigraphic sections shows that a complex depositional mosaic composed of wet meadows, seeps, flowing springs, streams, and wetlands covered the valley bottom during the last two glacial periods. Differences in ostracode species assemblages suggest that climate associated with the earlier discharge cycle (Unit B) was colder and perhaps wetter than that of the younger cycle (Units D and E). $\delta^{18}\text{O}$ values from >400 ostracode shells vary by $\sim 5\%$, and there is no consistent, section-wide, difference in isotopic values between standing water and spring taxa. This pattern strongly suggests short residence times for water in local basins, due to loss of water from basins by outflow as groundwater or overflow, rather than by evaporation.

We used the $\delta^{18}\text{O}$ value of fossil ostracodes to place constraints on paleotemperature in the valley bottoms during glacial periods. This analysis entails at least three key assumptions: no vital or evaporation effects during valve formation of the ostracode *Cypridopsis vidua*, short transit times in the aquifer, and the basic relationship between

modern air and spring water temperature holds for the past. If these and other assumptions are satisfied, we estimate that mean annual air temperature during the penultimate wet period (Unit B₂) in the valley bottom was at least 10.8 °C colder than today, and at least 5.6 °C colder during the last glacial maximum (Unit D). If a vital effect of 0.8–1‰ is assumed using $\delta^{18}\text{O}$ values from groundwater canionids, then the above estimates of maximum valley-bottom temperatures during Unit D time increase by ~2–3 °C.

INTRODUCTION

Major basins in the southern Great Basin are largely dry today because regional water tables remain below the surface and stream flow supported by snow-pack and high-mountain spring discharge is restricted. During the late Pleistocene, climate was wetter and cooler, and regional water tables were higher across the southern Great Basin, producing seeps, flowing springs and associated wet meadows, streams, and wetlands in the centers of the now largely dry basins (Quade, 1986; Quade and Pratt, 1989). As climate became drier and warmer during the Holocene, water tables fell, valley fill aquifers dried, and stream flow ceased, leading to dissection and extensive exposure of these spring-related deposits. The stratigraphy, paleontology, paleohydrologic, and paleoclimatic implications of the deposits have been the focus of many papers and maps (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989; Quade et al., 1995, 1998; Bell et al., 1998, 1999). These studies document the repeated change in regional hydrology over the past ~500,000 yr in response to regional climate change. Relative age estimates of these paleo-discharge periods are based largely on amino acid racemization/epimerization dating of fossil mollusks, while ^{14}C dates, largely from carbonized wood and organic mats, provide absolute age control on the younger deposits.

Geologists rely heavily on paleolake deposits and plant macrofossils from packrat middens to document changes in paleoclimate in the Great Basin. Spring-related deposits, however, offer another perspective that enjoys several advantages over the paleoenvironmental information available from lake deposits. Young (<15 ka) spring and wetland deposits can often be reliably radiocarbon dated from the remains of vascular plants, unlike lake sediments where carbon reservoir effects (e.g., Bischoff et al., 1997) or contamination problems associated with carbonates and organic matter make accurate age determination uncertain. Spring discharge and wetland deposits can also be studied in extensive natural exposures, providing the equivalent to multiple exposed “cores” in which the lateral continuity of a hydrologic event can be traced. Although caution must be exercised, the $\delta^{18}\text{O}$ values of carbonates from ostracodes and mollusks in spring deposits offer insights into the $\delta^{18}\text{O}$ values of the paleo-recharge. Because spring discharge represents flowing water, it is less likely to become evaporatively enriched than lake water and should have a $\delta^{18}\text{O}$ value close to the recharge value, commonly from winter precipitation (Winograd et al., 1998).

A key limitation of the spring-related sedimentary records is that the magnitude of hydrologic changes can only be semiquan-

titatively estimated. Springs produce a complex mosaic of aquatic environments including the flowing spring or seep areas themselves, wet meadows, streams, and wetlands. The aquatic environments responsible for the deposits do not leave bathtub rings as lakes do. Thus, they offer no means of quantifying the precipitation/evaporation balance related only to climate. In the case of the spring deposits we studied, isotopic and taxonomic evidence does show that evaporation was minor, but the causes are probably both climatic and topographic (i.e., the system overflowed). In contrast to lake hydrologic budgets, flow-dominated environments such as springs only provide insights into the limiting hydrologic conditions necessary for their genesis. So, one can only estimate what reduction in temperature and (or) rise in precipitation is necessary to raise the regional water tables to ground surface, recharge the valley fill aquifers, and produce stream flow. Actual conditions may greatly exceed the minimum needed to initiate surface discharge.

In this paper we synthesize new results from four stratigraphic sections with previous results from across the region. The new study sections include two (LPM-34 and OCI-11) from Corn Creek in the northern Las Vegas Valley, one (LPM-35) from near Cactus Springs, Nevada, and one (LWDD 6/8N) through diatomaceous deposits next to Highway 95 in the eastern Amargosa Valley, informally termed the “Lathrop Wells Diatomite” (Fig. 1). The new paleoenvironmental data includes tabulation of ostracode species by stratigraphic level and environmental preference, and stable isotope analyses of both ostracodes and aquatic mollusks, all placed in the context of new and extensive radiocarbon age control of the deposits. The ostracode data in particular provide an important new perspective on the sources, temperature, solute-composition, and solute-concentration (total dissolved solids, TDS) of the water that discharged in valley bottoms during wet periods. Finally, we combine our isotopic evidence with data on modern springs to place constraints on the maximum mean annual temperatures in valleys during wet periods.

LABORATORY METHODS

The sediment samples were processed for ostracodes according to technical procedure HP-78, R1, as described in Forester (1991a). Sections OCI-11 and LPM-35 were sampled continuously in 5-cm thick intervals, and each sample was divided in four parts. Ostracodes were picked from about a 15-g subsample of the 5-cm thick field sample. A second subsample of ~50 g was also prepared for multiple uses, such as stable isotope

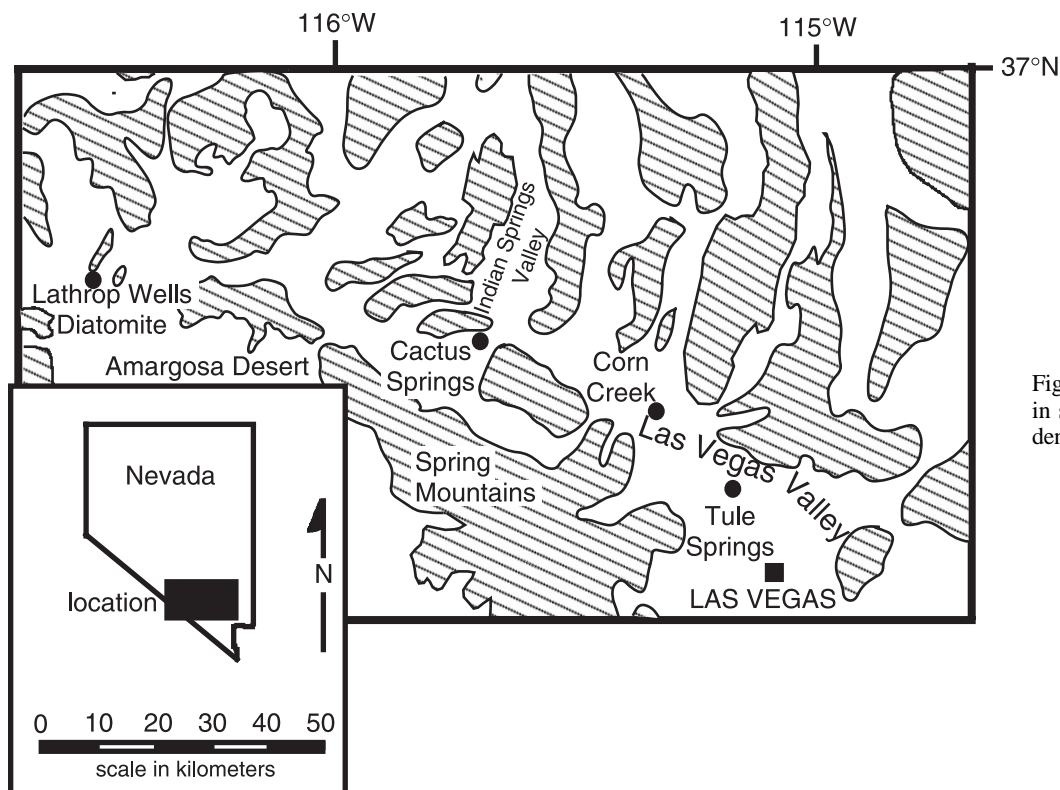


Figure 1. Location of study sections in southern Nevada. Patterned areas denote major mountain ranges.

or radiocarbon analyses. A third subsample of about five grams was taken for pollen extraction, but examination of a few of these samples suggests pollen is not commonly preserved. A fourth subsample was archived.

Fossil mollusks were handpicked and identified at the University of Arizona and at the U.S. Geological Survey, Denver. Specimens were washed repeatedly in an ultrasonic bath of distilled water until free of any adhering detritus, soaked in 2% H_2O_2 , washed, dried, and then separated for ^{14}C dating by taxa. Coiled taxa such as *Vallonia* were crushed and the shell fragments viewed under a microscope to insure no detritus was entrapped within. One to five shells were required for a ^{14}C date. One radiocarbon date also was obtained from ostracodes. All dating was by accelerator mass spectrometry through Beta Analytic, Inc.

Carbonized wood was used for dating of some horizons. Though identical in appearance to charcoal, carbonized wood differs by being much more soluble in base treatment. All samples were digested in 2–3N HCl for at least one hour, until effervescence stopped but pH remained <2 , and then thoroughly washed in distilled H_2O . Base treatment consisted of 2–3 soakings in 2–4% NaOH, followed by digestion and filtration, which generally resulted in near complete dissolution of the organic material. Humate solids were precipitated from the supernatant by acidification, followed by filtration, washing to a pH of ~ 3 and drying. Except where noted, the humate fraction was used for dating. Previous studies have shown this fraction to yield very reliable

dates (Quade et al., 1998). All dates are reported in ^{14}C years B.P., unless otherwise noted.

Ostracode and mollusk shell carbonate CO_2 was extracted with 100% H_3PO_4 at 75 °C in a Kiel automated extraction device, and $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were determined using a Finnigan MAT 251 mass spectrometer. For larger ostracode species, such as *Strandesia meadensis*, a single valve was sufficient for analysis, whereas for the smaller species, such as the groundwater taxa, an average of 8 valves were loaded. Mass spectrometer analyses were corrected to calcite or aragonite, as appropriate, by three-point calibration using calcite standards NBS-19 ($\delta^{13}\text{C}_{\text{PDB}} = 1.92\text{‰}$; $\delta^{18}\text{O}_{\text{smow}} = 28.65\text{‰}$), NBS-18 ($\delta^{13}\text{C} = -5.0\text{‰}$; $\delta^{18}\text{O} = 7.20\text{‰}$), and NBS-20 ($\delta^{13}\text{C} = -1.06\text{‰}$; $\delta^{18}\text{O} = 26.64\text{‰}$). The $\delta^{18}\text{O}_{\text{smow}}$ values of water samples were determined by $\text{CO}_2\text{-H}_2\text{O}$ equilibration according to procedures developed by Epstein and Mayeda (1953) and Kishima and Sakai (1980). Isotopic compositions were determined on a Finnigan MAT 252 mass spectrometer and the measured values corrected using a two point correction based on Standard Mean Ocean Water ($\delta^2\text{H}$ and $\delta^{18}\text{O} = 0\text{‰}$) and Standard Light Antarctic Precipitation ($\delta^2\text{H} = -428\text{‰}$; $\delta^{18}\text{O} = -55.5\text{‰}$) (Coplen, 1994).

RADIOCARBON DATING OF MOLLUSKS

Aquatic and terrestrial mollusks are locally abundant in spring deposits of all ages, and were extensively radiocarbon

dated in this study. Previously, most of the older (>14,000) spring-related deposits were undatable due to a lack of organic carbon. This motivated Brennan and Quade (1997) to explore the potential of mollusk aragonite for dating purposes. They found that small land snails in the deposits yield reliable ^{14}C ages, based on the similarity of ages between land snails and associated vascular plant remains. However, the more abundant aquatic snails yield ages that are often too old, due to incorporation of C from variably ^{14}C -deficient surface waters. The extent of this deficiency tends to be much less in glacial-age specimens than in Holocene ones. Brennan and Quade (1997) found that aquatic mollusks in this system are 0–3000 ^{14}C years older than the true stratigraphic age, less than the much larger (>10,000 yr) deficiencies observed by Riggs (1984) in the Ash Meadows system. Thus, the ages from aquatic snails provide maximum ages (by <3000 yr) for the deposits containing them. Exceptions to this generalization can occur when mollusks are reworked, such as within channels cutting through older deposits. However, deposits in our study sections formed mostly in low-energy wetlands and springs. Except at lower Corn Creek Flat, deep channel cutting and reworking of mollusks is rarely in evidence, and then only locally. Moreover, with few exceptions, fossil ostracodes and mollusks that we analyzed are fresh, without any signs of significant abrasion.

OSTRACODES IN SPRING-DISCHARGE AND WETLAND ENVIRONMENTS

Ostracodes are microscopic aquatic crustaceans with calcitic bivalved shells that are easily identified to genus and species. Particular ostracode species often live in limited hydrologic settings such as springs, streams, lakes, wetlands, and groundwater. Within such settings, the species are further limited by having life cycles that are dependent on certain physical and chemical parameters, including: (1) total dissolved solids (TDS), (2) major dissolved-ion composition and especially the total-alkalinity/calcium (alk/Ca) ratio, (3) water-temperature, (4) the daily to annual variability of all of the latter parameters, and (5) the permanence of the environment (Delorme, 1969; DeDecker, 1981; Forester, 1983, 1987, 1991a). Thus, the hydrologic setting, and the chemical and physical characteristics of the environment determine the species composition of ostracode assemblages. Identifying those assemblages in a stratigraphic sequence allows one to reconstruct past environments.

Lake and wetland species typically have biogeographic distributions that are related to climate. That is, the physical and chemical properties of the water in which those ostracodes live are often fully or partially determined by regional climate. Because these ostracodes routinely survive transportation from one place to another, their biogeographic ranges rapidly shift with climate-driven change of their environment.

Ostracodes that live only in springs also survive transportation. Unlike wetland or lake ostracodes, however, spring-discharge ostracodes may or may not reflect local climate conditions, because

the physical and chemical characteristics of spring discharge may not be directly linked to local climate (Forester, 1991a).

Conversely, geologically long-lived and environmentally stable aquatic settings such as Lake Baikal, or large regional aquifers such as the lower carbonate aquifer in southern Nevada, often support endemic ostracode species swarms. These endemic surface- or groundwater species either cannot survive transportation or, if they do, cannot establish populations in new environments (Forester, 1991b). The presence of endemic species indicates long-term stability of their environment.

The basis for reconstructing paleoenvironments using fossil ostracode data comes from ostracode species occurrence and associated environmental data in the literature (e.g., Delorme, 1989) and from an unpublished ostracode species environmental database. The unpublished database contains ~800 sites, primarily lakes, wetlands, and springs, from throughout the United States and ~30 sites from Mexico. The data were collected by various U.S. Geological Survey personnel, by Alison Smith and Don Palmer at Kent State University, and by Brandon Curry at the Illinois State Geological Survey. The ostracode database is used here to both evaluate the most likely hydrologic habitat(s), such as spring or wetland, and the chemical characteristics of the water from those habitats.

HYDROLOGICALLY COMPLEX DEPOSITIONAL ENVIRONMENTS

The heterogeneous distribution of seeps, springs, streams, and wetlands along a valley floor results in environmentally complex depositional environments. Consequently, sediment accumulation at different sites along a valley floor may reflect different environmental settings, somewhat analogous to sedimentary facies in large lakes or the ocean. Similarly, because various ostracode species live in different hydrological environments, the stratigraphic distribution of ostracode species assemblages will also vary with location along a valley floor.

The potential or likelihood of different horizons of the same age to record different hydrological histories must then be taken into account in an environmental interpretation. There are several ways in which to evaluate spatial-temporal heterogeneity: (1) study several stratigraphic sections from different sites in a valley to capture the complex spatial-temporal relations of the sedimentary environments, (2) focus on a more homogeneous environmental setting such as in the valley center, analogous to taking a core from the center of a lake, (3) study sections from different valleys to identify synchronous environmental change, which should reflect a regional response to climate, and (4) use the hydrological sensitivity of ostracodes or other proxies to filter spatial from temporal changes in stratigraphic sections. So, for example, a change from stream to spring ostracodes might reflect a facies change, whereas a change from cold to warm wetland taxa might reflect climate change. All four approaches were employed in this study, but with an emphasis on numbers 2 and 4.

MODERN AND FOSSIL OSTRACODES FROM SOUTHERN NEVADA AND EASTERN CALIFORNIA

Springs are the most common natural aquatic environment in southern Nevada today. Large high-flow warm springs discharge from the lower carbonate aquifer, whereas typically low-flow cool springs discharge from valley fill or other local aquifers (see Wino-grad and Thordarsen, 1975). Overall, aquatic environments in the region today are very restricted when compared to the extensive valley bottom wetlands that were common in the past. Modern-day sites somewhat analogous to the paleo-hydrology of southern Nevada do exist in northeast Nevada, in, for example, the Ruby and Steptoe Valleys (Quade and Pratt, 1989; Quade et al., 1995).

Ostracodes were collected from a number of the extant springs and wetlands in southern Nevada and eastern California, providing a basis for a region-specific comparison of modern to past taxa. Ostracodes were also collected from the Ruby Valley wetlands and in springs in the Ruby Mountains, allowing for a comparison of this modern area to the paleoenvironments from southern Nevada. Because the ostracodes serve as hydrologic proxies, comparison of modern and fossil ostracodes provide a way to compare modern and past hydrology.

A diverse group of species composes the fossil ostracode assemblages found in the deposits on the valley floors in southern Nevada. The high diversity (5–10 or more species) reflects the heterogeneity of aquatic environments that contributed to the setting in which the sediments were deposited. Twenty-eight endemic fossil groundwater species were also found in Pleistocene deposits throughout the region. The groundwater ostracodes probably discharged to the surface, where their shells were deposited with surface-water taxa.

The four sections (OCI-11, LPM 34, 35, and LLDW-6/8N) discussed in this paper contain several common surface-water and groundwater ostracode species. Common surface-water species are defined as those occurring in more than five samples, whereas the groundwater species abundances are summed together and reported as a single entity. Rare surface-water taxa are omitted from discussion, because their limited stratigraphic distribution does not offer any insight into the general characteristics of the past environment. Groundwater taxa are summed together to signify groundwater discharge from the regional aquifer, which is believed to be the source of these taxa. No other environmental information can be derived from the groundwater taxa, because they are endemic, mostly known as fossils, and, with the exception of springs in the area, no environmental data is available for them. Although the discussion treats the taxa from all four sections, the data from section OCI-11 is emphasized, because that section contains both the longest sedimentary record and the most extensive set of samples.

The ostracode species from OCI-11 are further sorted and presented according to one of three key environmental settings: springs, wetlands, and groundwater (Fig. 2). The spring category includes ostracodes known to live in seeps, flowing springs, and spring-fed pools and streams. The wetland category includes taxa

found in more extensive standing water bodies (marshes, ponds, littoral zones of small lakes) also chemically and perhaps thermally dominated by groundwater. No lacustrine taxa, in the sense of taxa found in standing water-bodies not dominated by groundwater, were found in these deposits. In some instances, species that commonly live in both wetlands and springs were placed in one environmental category in which they are believed to be more common. In other cases, such as with *Limnocythere parornata*, abundance was divided equally between the spring and wetland environmental categories, following its modern-day distribution. Creating ostracode stratigraphic profiles for both general habitat types (Fig. 2) and for particular taxa (Fig. 3) provides a way to illustrate general paleohydrologic change and the components of the general change.

STRATIGRAPHY, SEDIMENTARY UNITS, AND OSTRACODE PROFILES

In this paper, we follow the basic stratigraphic nomenclature for the region developed by Haynes (1967) from the Tule Springs archeological site northwest of Las Vegas (Fig. 1). The oldest deposits at Tule Springs are alluvial and designated Unit A, but are not recognized from other areas. Unit B is more widespread and consists of alluvial silt and sand, as well as green muds (Unit B₂) representing very extensive paleo-spring discharge. Unit B yielded mostly infinite ¹⁴C dates at Tule Springs, and is therefore thought to be >40,000 ¹⁴C yr B.P. A well-developed paleosol is often preserved at the top of Unit B. Unit C is entirely alluvial and not widely exposed. Unit C marks a dry episode between Units B₂ and D, both of which are derived from spring discharge.

Extensive green muds compose overlying Unit D and represent spring discharge and wetland development across the area, greater in extent than in Unit B₂ at Tule Springs. Previous dating control on Unit D comes from Tule Springs on carbonized wood (25,300 ± 2500 ¹⁴C yr B.P.; UCLA-539; Haynes, 1967) from the base of a spring feeder, and on large aquatic shells of *Planorbella subcrenata* (22,600 ± 550 ¹⁴C yr B.P.; UCLA-536) from the middle of Unit D. The shell date should represent a maximum age for middle Unit D deposition. Spaulding (1995), citing McVickar and Spaulding (1993), describe dates on charcoal of 26,800 ± 700 and 27,580 ± 650 ¹⁴C yr B.P. from somewhere in Unit D near Tule Springs. A thick marly caprock developed in the upper ~1 m of Unit D, probably as a result of the desiccation of Unit D wetlands prior to Unit E deposition.

Unit E caps Unit D, and like Unit D was deposited in spring-fed channels and wetlands, but over a smaller area. Unit E is further subdivided into Units E₁ (14.5–11 ¹⁴C ka), characterized primarily by deposits derived from spring-fed channels, and Unit E₂ (11.3 to ca. 7.2 ¹⁴C ka), characterized by black mats and some channel deposits, except for the uppermost part of the unit. Uppermost Unit E₂ consists of brown silt capped by gravel that together are typically 0.5–1 m thick. Complete desiccation of permanent surface moisture associated with Unit E₂ occurred in most sections by ca. 8–7 ¹⁴C ka.

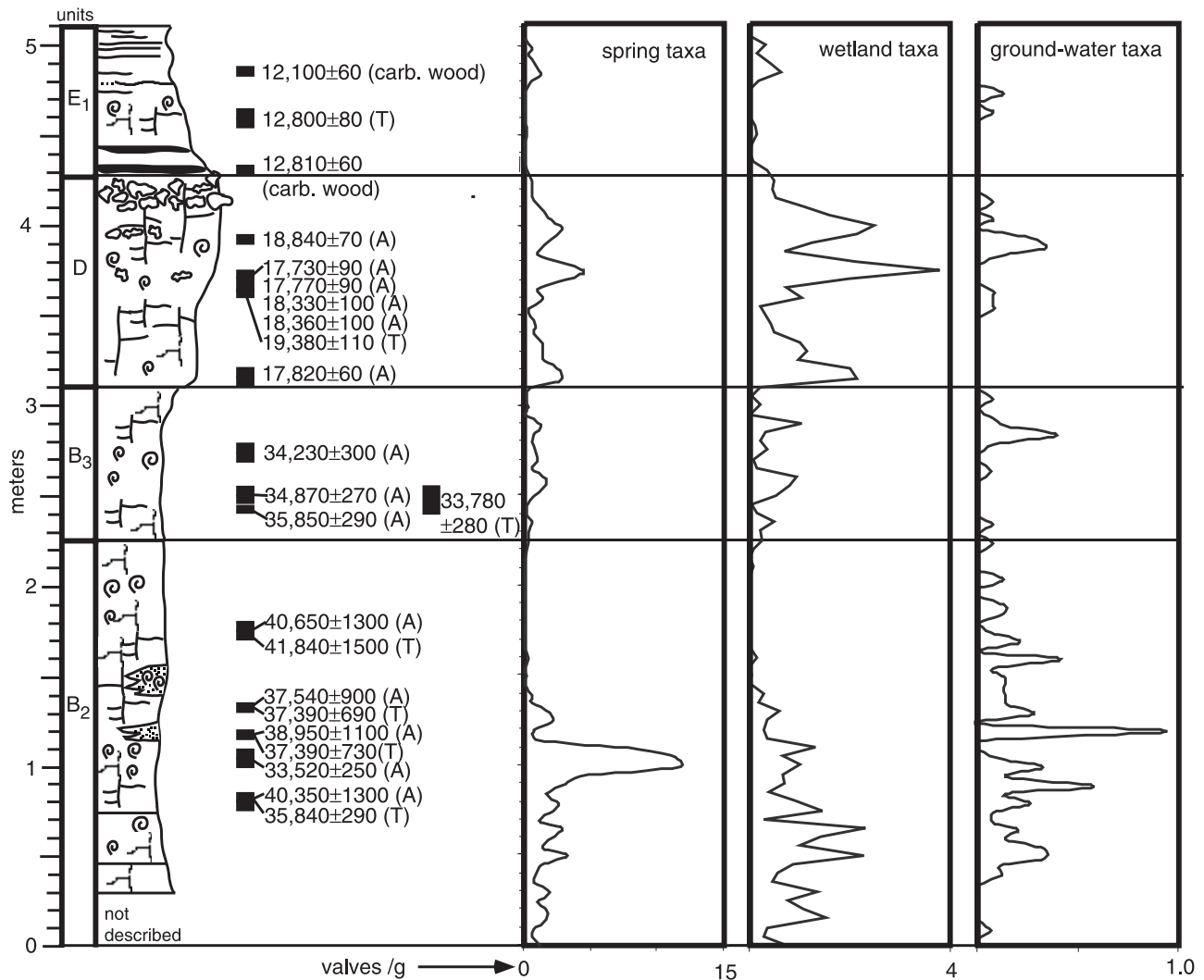


Figure 2. Stratigraphic section, units, and radiocarbon dates from OCI-11 in lower Corn Creek Flat (115°20'48", 36°23'21"). See Figure 4 for explanation of lithologic symbols. Columns to right depict ostracode valves/gram of sediment, divided on the basis of ostracode environmental preferences. See text for explanation. A—aquatic mollusks, T—terrestrial mollusks.

In our study sections, Unit B and Unit D crop out only on lower Corn Creek Flat and probably in the eastern Amargosa section, whereas Unit E is present in all sections.

Corn Creek Flat sections OCI-11 and LPM-34

Two sections, OCI-11 and LPM-34, were described and sampled from Corn Creek Flat. These sections are located ~200 m apart in a small cluster of badlands near the bottom (southeast) end of the flat just before entering the narrows that connect to Tule Springs Flat to the south (see Quade et al., 1995, Figure 6A, or Bell et al., 1999, for a detailed map of the area). These sections were selected for their valley center location, which was thought would provide the most aquatic setting, and for their stratigraphic thickness of 3–5 m.

Section OCI-11

Unit B₂ (0–225 cm). The lower 225 cm is mostly pale green (5Y 6/3d) to brown (10 YR 6/3d) silt with little primary bedding, cut by a few small, sandy partings (Fig. 2). The locally reduced color, fine-grain size, and lack of bedding are typical of wetland deposits in the region, a characterization confirmed by the faunal assemblages discussed below.

The nine ¹⁴C dates (five on aquatic and four on terrestrial snails) from five horizons fall between 33,520 ± 250 and 41,840 ± 1500 ¹⁴C yr B.P. (Table 1; Fig. 2). Two lines of evidence suggest that the dates represent minima. First, Brennan and Quade (1997) obtained a date of 40,310 ± 310 on pre-Wisconsin age snails from spring deposits in the Pahrump Valley, showing that a demonstrably infinite-age shell is slightly contaminated with

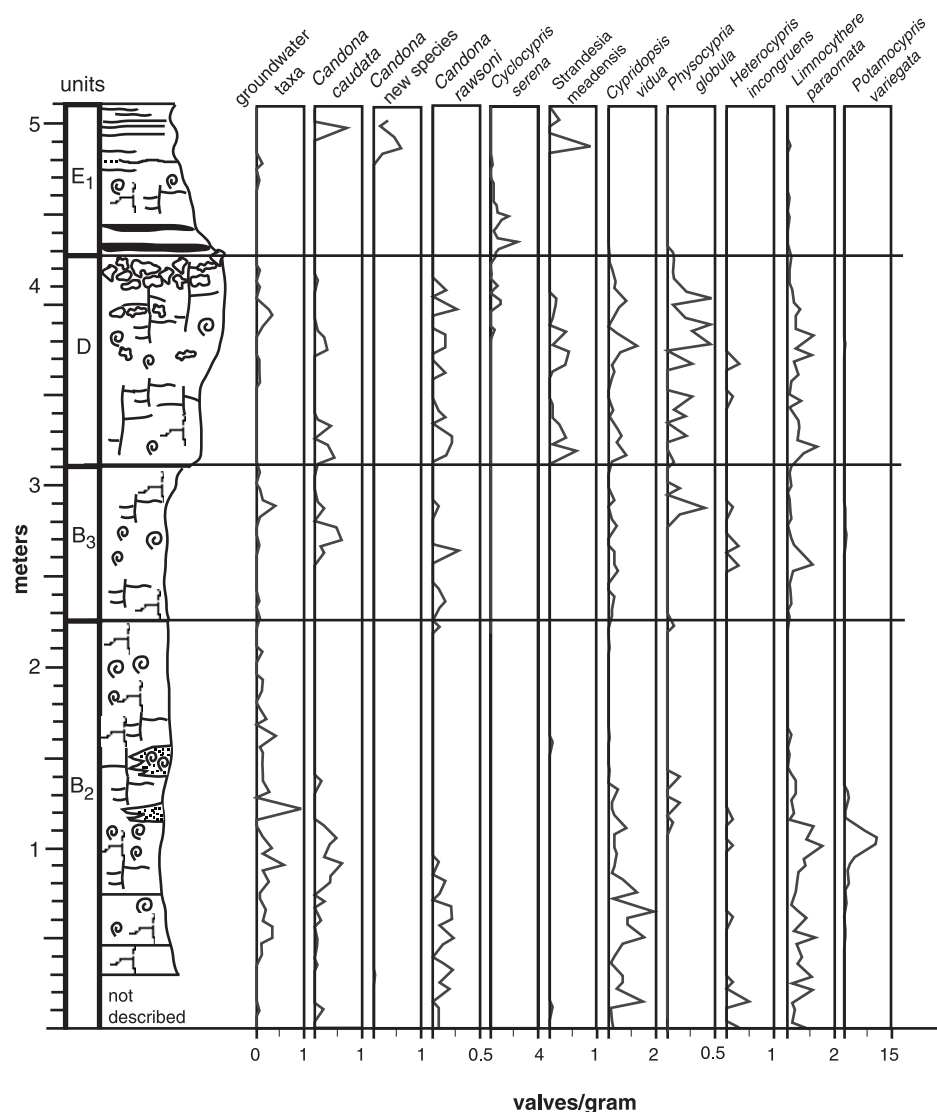


Figure 3. Stratigraphic section, units, and ostracode taxa from OCI-11 in lower Corn Creek Flat (115°20'48", 36°23'21"). See Figure 4 for explanation of lithologic symbols.

young ^{14}C . Second, the dates follow no stratigraphic order, suggesting that the age differences arise from variable but slight (<1.5% modern) contamination.

We assign sediments in this interval to Unit B₂. This is based on the ^{14}C results and position at the base of the section, the same basal position occupied by Unit B₂ at Tule Springs.

Unit B₂ was deposited in three basic environmental settings based on the ostracode data: a wetland, a stream and flowing spring, and a wet-meadow (Fig. 2). The basal sediments in Unit B₂ (0 to ~75 cm) contain predominately wetland taxa, whereas the middle of Unit B₂ (~75 to ~125 cm) contains predominately spring/stream taxa. The upper part of Unit B₂ (~125 cm to ~225 cm) contains rare groundwater and scattered surface-water ostracode taxa (Fig. 2) and abundant aquatic gastropods. Groundwater taxa are most abundant in the basal through the middle part of unit B₂ compared to the rest of the section. This implies that the regional water table was both higher

than today, and was discharging at a higher rate relative to the rest of the record in this section.

The ostracodes from basal Unit B₂ (0 to ~75 cm) provide additional insights into the chemical and temperature characteristics of the water, and from that, an indication of how climate in this period differed from the later periods. *Cypridopsis vidua*, *Candona rawsoni*, and to a lesser extent *Limnocythere paraornata* are wetland taxa in the basal part of unit B₂ (Fig. 3). Conversely, other wetland taxa, such as *Cyclocypris serena* and *Physocypria globula*, are common in the younger part of the section, principally Unit D, but are absent from the basal part of Unit B₂. All of these wetland species co-occur in the younger part of this section, and are known to live together at many, but not all, sites today. Therefore, the absence of *C. serena* and *P. globula* in the older part of the section is probably not related to differences in water-chemistry, but instead to differences in wetland hydrology and perhaps to seasonal water temperatures in the case of *P. globula*.

TABLE 1. ^{14}C DATES FROM STUDY SECTIONS IN SOUTHERN NEVADA

Sample	Beta #	Sampling interval (cm)	^{14}C date	$\delta^{13}\text{C}$ (PDB)	Material
<u>Section 186/187</u>					
CSCarb. 27b	73966		12,400 \pm 60	-26.5	Carbonized wood
CSCarb. 28a	73967		12,410 \pm 60	-27.0	Carbonized wood
CSCarb. 28b	73968		12,490 \pm 50	-26.6	Carbonized wood
CSCarb. 30b	73969		12,180 \pm 110	-28.7	Carbonized wood
<u>Section OCI-11</u>					
CSC-29b	84316	490	12,100 \pm 60	-26.7	Carbonized wood
NV94RMF86CL+CM	84781	445-450	12,800 \pm 80	-8.3	Terrestrial: <i>Vallonia cyclophorella</i>
CSC-27b	84315	430	12,810 \pm 60	-27.2	Dispersed organic matter
NV94RMF86BY	91926	390-395	18,840 \pm 70	-7.3	Aquatic: <i>Pisidium</i> sp.
NV94RMF86BU	84780	370-375	17,730 \pm 90	-6.0	Aquatic: <i>Pisidium</i> sp.
NV94RMF86BT	84776	365-370	17,770 \pm 90	-6.9	Aquatic: <i>Pisidium</i> sp.
NV94RMF86BT	84777	365-370	18,330 \pm 100	-6.7	Aquatic: <i>Pisidium</i> sp.
NV94RMF86BT	84778	365-370	18,360 \pm 100	-5.2	Aquatic: <i>Strandesia meadensis</i>
NV94RMF86BS+BT+BU	84779	360-375	19,380 \pm 110	-8.9	Terrestrial: <i>Vallonia</i> sp. + <i>Pupillid</i>
CSC-25	86430	310-320	17,820 \pm 60	-10.5	Semi-aquatic: <i>Stagnicola</i> sp.
CSC-14	86425	260-270	34,230 \pm 300	-9.6	Aquatic: <i>Gyraulus parvus</i>
NV94RMF86AU+AT	85985	240-250	34,870 \pm 270	-6.9	Aquatic: <i>Pisidium</i> sp.
NV94RMF86AS	85984	235-240	35,850 \pm 290	-6.7	Aquatic: <i>Pisidium</i> sp.
NV94RMF86AU+AT+AS	85981	235-250	33,780 \pm 280	-9.2	Terrestrial: <i>Vallonia</i> sp. + <i>Pupillid</i>
NV94RMF86AE+AF	84774	160-170	40,650 \pm 1300	-7.2	Aquatic: <i>Pisidium</i> sp.
NV94RMF86AE+AF	84775	170-180	41,840 \pm 1500	-8.1	Terrestrial: <i>Vertigo berryi</i> + <i>Vallonia</i> sp.
NV94RMF86W	84784	130-135	37,540 \pm 900	-7.0	Aquatic: <i>Pisidium</i> sp.
NV94RMF86W	83993	130-135	37,390 \pm 690	-9.5	Terrestrial: <i>Vallonia</i> sp.
NV94RMF86T	84783	120-125	38,950 \pm 1100	-7.0	Aquatic: <i>Pisidium</i> sp.
NV94RMF86T	83994	120-125	37,390 \pm 730	-9.4	Terrestrial: <i>Vallonia</i> sp.
CSC-16	86426	100-110	33,520 \pm 250	-10.7	Aquatic: <i>Gyraulus parvus</i>
NV94RMF86M+L	84782	85-90	40,350 \pm 1300	-6.5	Aquatic: <i>Pisidium</i> sp.
NV94RMF86M+L	85986	85-90	35,840 \pm 290	-8.3	Terrestrial: <i>Vallonia</i> sp. + <i>Pupillid</i>
<u>LPM-34 (floating section)</u>					
RMF93NV71d, -0.25m	74329	75-80	16,390 \pm 70	-7.3	Aquatic: <i>Pisidium</i> sp.
RMF93NV71d, -0.25m	76433	75-80	18,850 \pm 100	-8.7	Terrestrial: <i>Vallonia</i> sp.
RMF93NV71g, -0.75m	76434	25-30	25,340 \pm 180	-7.7	Terrestrial: <i>Vallonia</i> sp.
RMF93NV71f, -1.00m	74330	0-5	26,620 \pm 160	-7.2	Aquatic: <i>Pisidium</i> sp.
<u>LPM-35</u>					
Cac.Spr.Carb.8	86427	330	10,030 \pm 60	-26.7	Carbonized wood
Cac.Spr.QUADE90-100	86429	185-195	12,300 \pm 60	-7.4	Terrestrial: Succineidae
Cac.Spr.QUADE45-55	86428	140-150	12,890 \pm 60	-9.2	Aquatic: <i>Gyraulus circumstriatus</i>
NV94RMF84O	83992	137-142	13,350 \pm 60	-8.2	Terrestrial: <i>Pupilla muscorum</i>
NV94RMF84N	83995	130-137	13,690 \pm 80	-7.9	Terrestrial: <i>Euconulus fulvus</i>
NV94RMF84N	83991	130-137	13,270 \pm 260	-7.5	Terrestrial: <i>Pupilla muscorum</i>
NV94RMF84N	83988	130-137	13,420 \pm 60	-8.1	Terrestrial: <i>Vertigo berryi</i>
NV94RMF84M	83989	125-135	13,630 \pm 60	-8.4	Terrestrial: <i>Euconulus fulvus</i>
NV94RMF84M	83990	125-135	13,560 \pm 60	-8.5	Terrestrial: <i>Pupilla muscorum</i>
<u>Lathrop Wells Diatomite</u>					
LWD-7 (lower)	84448	490-500	13,970 \pm 140	-8.3	Aquatic: <i>Gyraulus circumstriatus</i>
LWD-7	83708	490-500	13,480 \pm 120	-7.4	Terrestrial: Succineidae
LWD-7	83709	490-500	13,510 \pm 120	-8.7	Terrestrial: <i>Vertigo berryi</i>
LWD-7	83710	490-500	13,890 \pm 140	-8.6	Terrestrial: <i>Vallonia</i> sp.
LWD-7	83495	490-500	14,080 \pm 120	-7.4	Aquatic: <i>Pisidium</i> sp.
LWD-7	83496	490-500	13,550 \pm 140	-8.5	Terrestrial: Succineidae
LWD-12	90244	70-80	41,910 \pm 1860	-8.3	Terrestrial: <i>Vertigo berryi</i>
LWD-12	91922	70-80	39,970 \pm 1280	-9.0	Aquatic: Hydrobiidae
LWD-12	91923	70-80	35,120 \pm 700	-7.7	Aquatic: Hydrobiidae
LWD-12	91924	70-80	38,240 \pm 1020	-7.4	Aquatic: <i>Pisidium</i> sp.
LWD-12	91925	70-80	36,880 \pm 900	-7.3	Aquatic: <i>Pisidium</i> sp.

The wetland species *C. vidua* and *C. rawsoni*, as well as the spring (seep) species *Heterocypris incongruens*, often live in ephemeral environments, whereas *C. serena* and *P. globula* are typically, but not exclusively, found in permanent (less ephemeral) wetlands and lakes. The ephemeral characteristic could be as frequent as annually, or as infrequent as several drought years within a decade. Because the sediments of Unit B₂ are widely distributed throughout the basin, the wetlands were extensive, but if the wetlands were also ephemeral, then either their source (input) waters were also ephemeral (seasonal?) or evaporation (output) increased seasonally for the case of a high-frequency ephemeral setting. Alternatively, the record may indicate that wet years were punctuated by drought years, in the case of a low-frequency ephemeral environment. The $\delta^{18}\text{O}$ results discussed below do not support seasonal or interannual increases in evaporation (drought).

Basal Unit B₂ also contains *Candona caudata*, but in lesser abundance than the collective wetland taxa (Fig. 3). It tends to live in permanent flowing water. Groundwater taxa, although not as common as the surface-water taxa, persist throughout the interval.

The complete species assemblage collectively indicates that this period was one in which the regional water table rose above ground surface on some basis, probably seasonally, resulting in the appearance of extensive wetlands with flowing springs or small streams among the wetlands. The ostracodes indicate the water had a low TDS, below ~1000 mg/L, and that the solutes never evolved to a saline-solute composition, and so was a water whose solutes were dominated by calcium bicarbonate (Forester, 1991a). Overall, the ostracode assemblage is composed of eurythermic species indicating that water temperatures varied during the year. Summer warmth-loving ostracodes such as *Physocypris globula* are absent or rare, implying summer water temperatures were typically below ~18 °C. Cold-requiring ostracodes such as *Prionocypris canadensis* and *Cavernocypris wardi* (Forester, 1991a), which live in high mountain springs in the region, are also absent or rare, implying that seasonal water temperatures were above ~12 °C.

Ostracodes from the predominately spring/stream environments of the next highest subunit (75 to 125 cm) of Unit B₂ also provide insight into the nature of that environment. The predominant spring/stream ostracode in this interval is *C. caudata*, whereas *Strandesia meadensis* is absent (Fig. 3). That occurrence pattern is probably significant in that *S. meadensis* lives in flowing springs, but is not common in streams, whereas *C. caudata* lives both in flowing springs and in streams. The presence of abundant *C. caudata* therefore implies that this interval of Unit B₂ was deposited in a stream-dominated environment or an environment with greater flow than is typical of a flowing spring.

The change from a wetland-dominated to a stream-dominated environment between the basal and middle subunits of B₂ may indicate increased discharge related to climate change, or it could simply reflect a local facies shift as a stream migrated across the valley floor. The ostracode *Potamocypris variegata* is extremely abundant in this subinterval (Fig. 3), but provides little environmental information, because it has not been found

commonly in North America. In Europe, it is known from both stream and wetland environments. The groundwater taxa are common throughout unit B₂, but are especially common in the two subintervals (0–75 and 75–125 cm) discussed above. The abundance of the groundwater taxa in these two subintervals implies that the regional water table was near the earth surface and was actively discharging.

The assemblage of ostracode species from 75 to 125 cm suggests that the water chemistry was fresh and TDS was typically below ~750 mg/L and, as with the lower unit, the solutes were dominated by calcium bicarbonate. The water temperature, based on all the sites where *C. caudata* occurs, falls into a large range from ~6 to 34 °C, so water temperature is not defined by the most common species for which there is modern data. If, however, only the occurrences near the Ruby Marsh (the probable modern analog) are considered, then the water temperature was between ~10 and 14 °C.

The third and youngest subinterval of Unit B₂ (~125 cm to ~225 cm) contains few to no ostracodes (Fig. 3), but aquatic gastropods are common. The presence of aquatic gastropods demonstrates that water was present, but the general absence of surface-water ostracodes implies that surface water bodies do not persist long enough to have the site fully populated by ostracodes. The wet meadow environment is one such environment where aquatic gastropods are common, but ostracodes are rare to absent (Quade et al., 1998), so it is the likely environment of deposition for these sediments.

The rich mollusk assemblage from Unit B₂ provides a much less detailed but congruent picture of a wetland environment depicted by the ostracodes. Mollusks are dispersed throughout most of the unit, but particularly abundant at 65–90, 110–130, and 190–220 cm. Although no exact counts of shells were made, aquatic mollusks far outnumber terrestrial ones. The presence of many large shells of *Planorbella subcrenata*, as well as of *Physa* sp., *Valvata humeralis*, *Pisidium* sp., and *Gyraulus parvus*, attest to the permanently aquatic character of some of Unit B₂ deposits. *P. subcrenata*, in particular, is not common in spring deposits in the southern Great Basin and is largely confined to the pond facies of Units D and B (Taylor, 1967; Quade et al., 1995). The presence of a few terrestrial snails attests to the nearness of dry banks to the site.

Unit B₃ (225–310 cm). This unit consists entirely of massive, pale-green (5Y 7/2d), hard, fine to medium silt. The upper and lower contacts are sharp and smooth. Four ¹⁴C dates from two horizons range from 33,780 ± 280 to 35,850 ± 290 yr B.P. (Table 1; Fig. 2). The dates do fall in stratigraphic order and the youngest date is from a terrestrial snail, which is to be expected of finite dates. However, these results overlap the youngest date from Unit B₂, suggesting that all the dates may be slightly contaminated infinite-age dates. The true age of this unit remains unclear; based on available evidence we view it as >33,780 ¹⁴C yr B.P. Aquatic mollusks are dispersed throughout the unit but were not identified.

Sediments of Unit B₃ (Fig. 2) contain ostracode taxa that imply a variable environmental sequence. The basal sediments

from ~225 cm to ~260 cm variously contains few to no ostracodes. The wetland ostracodes in this interval imply the wetland was ephemeral, like the wetlands from the basal Unit B₂ (0–75 cm). The presence of aquatic gastropods in intervals with few to no ostracodes implies a wet-meadow environment, with sufficient water to support gastropods, but not ostracodes. Ostracodes indicating flowing water, such as *Candona caudata*, appear at ~260 cm and persist until ~290 cm (Fig. 3). As with the flowing-water intervals in Unit B₂, this flow was more likely in a stream than in flowing springs, and could represent either a climate-driven change in discharge or a local facies shift unrelated to regional changes.

A wetland environment developed at this site in upper Unit B₃ (280–310 cm). This wetland, however, contains ostracode species that did not occur or were not common in the older wetland environments. Taxa such as *Cyclocypris serena* appear for the first time and *Physocypris globula* becomes common. *Cypridopsis vidua*, *Candona rawsoni*, and *Limnocythere paraornata* are also present. Groundwater taxa are also quite common and imply the regional water table was high and actively discharging, supporting the wetlands. The appearance of *C. serena* indicates, in part, a more permanent wetland that probably supported subaquatic macrophytes. The commonness of *P. globula* is also important, because it implies summer water temperatures were warmer than in the older wetlands. Permanence of the wetland during the summer is an alternative explanation to warmer summer water temperatures.

Ostracodes are only abundant in the uppermost (~280–310 cm) subunit of Unit B₃. The common species from this upper interval, when considered collectively rather than by sample content, imply a freshwater environment with TDS values largely below 750 mg/L and probably below ~500 mg/L. Solute composition is dominated by calcium bicarbonate and the alk/Ca ratio is low, reflecting carbonate solute-source rocks (Forester, 1987). Water temperatures vary with season and unlike the older intervals, summer water temperatures were warm and likely remain in the high teens and low twenties celsius for two or more months during the year. Winter water temperatures are cool and perhaps similar to those in the Ruby Valley (northeast Nevada), where many of the taxa found in this subinterval live today, and where winter water temperatures are below ~12 °C.

Unit D (310–428 cm). Unit D consists entirely of pale-green (5Y 8/1–8/2d), hard, fine to medium silt in the lower part and browner silt above 385 cm. Six ¹⁴C dates from this unit range from 19,380 ± 110 to 17,730 ± 90 ¹⁴C yr B.P. (Table 1; Fig. 2). The oldest date comes from land snails (four shells combined), while the other dates are from aquatic snails. This pattern of ages would imply some mixing or reworking of shells. As such, the middle of Unit D at this location is at least as old as 17,770 ± 90 but no older than 19,380 ± 110.

Support for this 19–17 ¹⁴C ka age range for Unit D comes from dates on reworked land snails in a Unit E₁ (<14,530 ± 80 ¹⁴C yr B.P. based on dates from carbonized wood) channel cut

directly into Unit D, located ~20 m to the west of OCI-11 (profiled in Quade, 1986, Figure 6). The terrestrial mollusks from this channel fill returned ages of 16,660 ± 70, 16,895 ± 170, 16,895 ± 170, 18,180 ± 90, 18,820 ± 90, and 21,260 ± 90 ¹⁴C yr B.P. (Brennan and Quade, 1997). This range of ages overlaps the dates from in situ mollusks described above, and may be the best representation of true age range of Unit D.

Abundant carbonate nodules appear for the first time in the section in the upper ~50 cm of Unit D. This carbonate is a conspicuous feature of Unit D in the described sections at Tule Springs (Haynes, 1967) and elsewhere (Quade et al., 1998). It probably represents capillary fringe/pedogenic cementation along this surface following the desiccation of Unit D wetlands, which occurred after 17,730 ± 90 (this paper) but before 14,450 ± 80 ¹⁴C yr B.P. (Quade et al., 1995).

The taxa from Unit D indicate that the depositional setting was a complex of flowing springs and wetlands (Fig. 2). Taxa such as *Cyclocypris serena* and *Physocypris globula* are common (Fig. 3) and indicate a relatively permanent and seasonally warm wetland environment. Unit D also contains two prominent abundance peaks of *Candona caudata*, indicating flowing water, but unlike the older occurrences of this taxon, these occurrences are associated with *Strandesia meadensis*. The presence of *S. meadensis* probably indicates flowing springs rather than streams. A possible shift from stream flow to spring flow may represent a change in discharge intensity linked to climate or simply a shift in hydrofacies. We favor the climate explanation because of the similarity of the ostracode assemblage of Unit D at OCI-11 to that of section LPM-34, a nearby section discussed below.

The collective ostracode species found in the Unit D samples imply that the environment was similar to that described above for the upper subunit of Unit B₃. The water is fresh with a TDS generally below 750 mg/L and probably 500 mg/L. Solutes are dominated by calcium bicarbonate, and temperatures vary seasonally. Summer water temperatures are in the high teens through low twenties celsius and winter temperatures are below ~12 °C.

Unit E₁ (428–510 cm). Unit E₁ consists of interbedded brown (10 YR 8/1d) silt and thin organic-rich layers in the lower part, and interbedded fine sand and silt above 470 cm. Overall, Unit E is more bedded and coarser than underlying Unit D. The basal contact is sharp and smooth.

Three dates were obtained on the humate fraction of two organic layers, one from the base of Unit E₁ that yielded a date of 12,810 ± 60 and another from carbonized wood at ~465 cm that returned a date of 12,100 ± 60 ¹⁴C yr B.P. The date of 12,800 ± 80 on terrestrial mollusks from 455 to 465 cm confirms the accuracy of ¹⁴C dates on such samples. These Unit E₁ sediments represent onlap along the margins of a deeply incised channel of Unit E₁ that dates to 14,530 ± 80 ¹⁴C yr B.P. at the base (Brennan and Quade, 1997).

Unit E₁ contains a few wetland ostracodes in the basal part of the unit, associated with the organic-rich layers (Fig. 2).

These taxa include *Cyclocypris serena* (Fig. 3) and *Limnocythere paraornata*, indicating some similarity with the Unit D wetlands. There are also samples scattered throughout Unit E₁ with aquatic mollusks but no ostracodes, implying a wet-meadow environment. There is also a number of species indicating flowing water, especially toward the top the Unit E₁ (Fig. 2). This includes *Candona* n. sp. 1, known to live in wetlands and springs in the region today, as well as *C. caudata* and other rare taxa that are not shown in Figure 3, as noted at the beginning of the ostracode discussion above. One of the taxa not shown in Figure 3 is believed to be a new genus and a new species and it is only known today from a high mountain stream above Cedar City, Utah. Its presence here may imply cold flowing water. Remarkably, even though Unit E represents deposition during a late glacial climate in transition toward interglacial climate, the setting is a cold-flowing stream.

Environmental information is not available for all of the ostracodes that are common in this unit. However, the apparent cold-flowing nature of the environment in which the upper part of Unit E₁ was deposited, together with taxa for which environmental information is available, indicates a fresh, probably dilute calcium bicarbonate water. The water may have had a TDS below 300 mg/L. Water temperatures probably did not vary a great deal seasonally due to flow and were probably <15 °C.

Section LPM-34

LPM-34 (Fig. 4) is located ~200 m downvalley from OCI-11, and provides a test of the lateral continuity of the major units seen in OCI-11. Only nine faunal samples were taken at LPM-34, and three horizons ¹⁴C dated. Green silt similar in appearance to Units B₂ and D makes up the basal ~30 cm of the section. Mollusks yielded ages of $26,620 \pm 160$ (aquatic) at the base and $25,340 \pm 180$ ¹⁴C yr B.P. (terrestrial) at the top of the exposed unit (Table 1; Fig. 4). These ages suggest a basal Unit D equivalence.

The silts are sharply truncated by channel sand and gravel containing mammalian bone and abundant mollusks. The sand fines upward gradually into pale-green silt. Mollusks from ~75 cm returned dates of $16,850 \pm 100$ (terrestrial) and $16,390 \pm 100$ ¹⁴C yr B.P. (aquatic). The sediment and character of the mollusks strongly resemble those of Unit D in OCI-11, and these dates would support that correlation. This also supports evidence discussed previously that Unit D is as young as ca. 16.4 ¹⁴C ka.

Unit E overlies Unit D along a sharp contact at 290 cm. Although we have no dates on this horizon, the presence of organic matter, bedded layers, and brown color all point to Unit E.

LPM-34 was coarsely sampled at 25 cm intervals to provide general information about the ostracodes in the section. The ostracode data is summarized in terms of wetland, spring, and

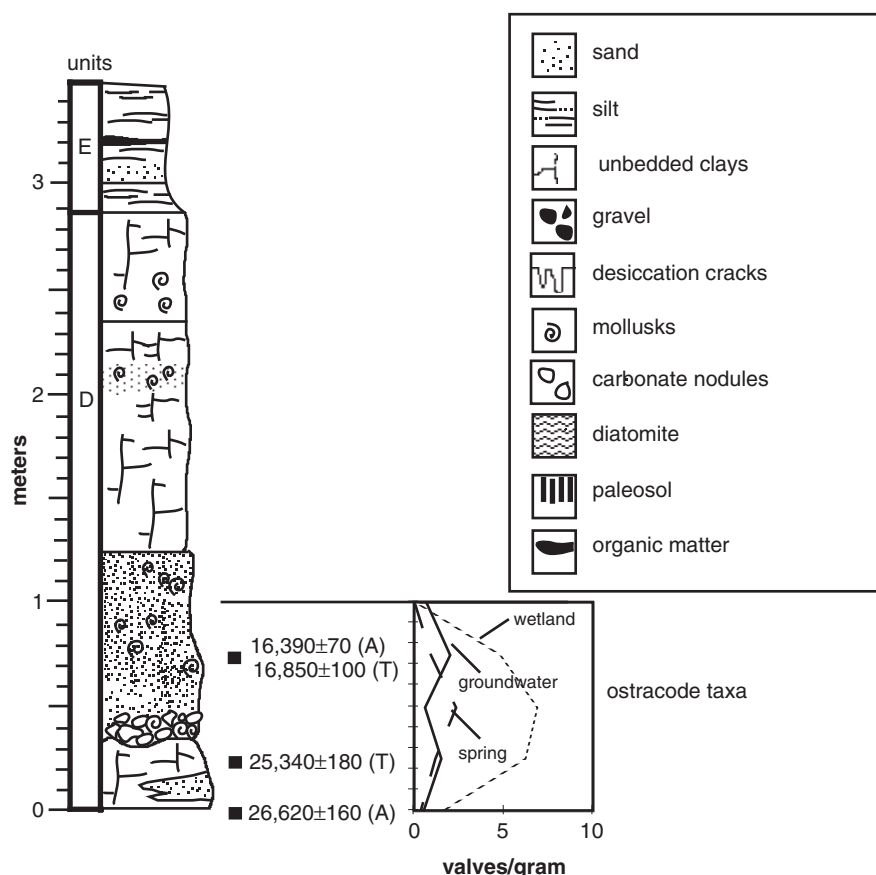


Figure 4. Stratigraphic section, units, and radiocarbon dates from LPM-34 in lower Corn Creek Flat (115°20'39", 36°23'16"). A—aquatic mollusks, T—terrestrial mollusks.

groundwater taxa and then plotted against the stratigraphic section for lower Unit D (Fig. 4). Like section OCI-11, the ostracodes that commonly lived in both the wetlands (standing water), springs (flowing water), and groundwater are all represented.

Ostracodes indicating several different types of hydrologic environments are most abundant in the basal part of Unit D, especially in the lower 75 cm. At 100 cm, the abundance of surface-water ostracodes is lower and groundwater taxa are common. Above 100 cm, aquatic gastropods are common, but ostracodes are rare, indicating a transition from wetlands and flowing springs (lower 75 cm) to a wet-meadow environment.

The ostracode species that dominate the assemblage in the lower 75 cm of section LPM-34 include wetland taxa such as *Cyclocypris serena*, and *Physocypris globula*, as well as spring and stream taxa such as *Candona caudata* and *Strandesia meadensis* (see Fig. 4). This is the same species assemblage as that which lived in the Unit D wetlands described above for section OCI-11. These taxa indicate that the wetlands consisted of standing and flowing water with the flowing water coming primarily from springs rather than streams. The presence of *P. globula* implies that summer water temperatures were warm, in the high teens to low twenties celsius. As with Unit D in section OCI-11, the environment associated with this subunit is fresh water and the solutes are dominated by calcium bicarbonate.

The transition from environments with surface-water taxa to those with few ostracodes, but common aquatic gastropods, may depict a simple change in hydrofacies or a shift in toward a drier and/or warmer climate. In section OCI-11, the environment of Unit D remained a wetland until the transition to Unit E, whereas at this site (LPM-34) Unit D appears to be a wet-meadow at the Unit D to E transition. The differences in transitions may be due to erosion (prior to Unit E deposition) of the top of Unit D at OCI-11, which is supported by the radiocarbon ages. These two sections are ~200 m apart and yet preserve somewhat different histories, illustrating the need to examine several sections to acquire complete environmental histories.

Cactus Springs section LPM-35

LPM-35 was selected for study because of its basin center location near Cactus Springs (Fig. 1) and thickness of 4.3 m. Section LPM-35 is the same as locality 1 in Figure 3 of Quade and Pratt (1989). The lowest unit is 90 cm thick and is composed of pale-green sand alternating with unbedded silt (Fig. 5). No dates were obtained from this unit, but it probably represents either Unit D or more likely lower Unit E₁.

Clay, silty clay, and local sandy layers dominate the interval 90–230 cm. The lower (90–160 cm) portion is mostly pale-green (5Y 7/2d) clay and silty clay containing abundant ostracodes, and aquatic, semiaquatic, and terrestrial mollusks. Six ¹⁴C dates on terrestrial snails range from 13,690 ± 80 in the middle of the unit to 13,350 ± 60 ¹⁴C yr B.P. Semiaquatic mollusks sampled 10 cm below the top returned a date of 12,890 ± 60 ¹⁴C yr B.P. (Fig. 5). A very weak soil appears to be developed on top of this interval at

150–160 cm, represented by Fe-staining, carbonate nodules, and a fine prismatic structure.

The upper 160–230 cm of the unit is composed of a basal sand capped by white (10YR 8/2d) silty clay. Terrestrial mollusks near the base of this interval gave a date of 12,300 ± 60 ¹⁴C yr B.P. Mollusks are common in the lower 20 cm, then decrease upwards. Staining and extensive insect bioturbation probably denote weak pedogenesis of this unit prior to burial by brown silt.

The upper 230–430 cm is composed of finely bedded brown silt over most of the interval, capped by 30 cm of coarse gravel. Mollusks and ostracodes are entirely absent. A date of 10,030 ± 60 ¹⁴C yr B.P. from dispersed carbonized wood fixes the age of the middle of the brown silt unit, and suggests that much if not all of this horizon belongs to Unit E₂.

The wettest part of the exposed record was being deposited no later than 13,560 ± 60 and continued through at least 12,890 ± 60 ¹⁴C yr B.P. Persistent but declining moisture is indicated until shortly after 12,300 ± 60. Sometime between 12,300 ± 60 and 10,030 ± 60 ¹⁴C yr B.P., standing surface moisture completely and permanently disappeared.

LPM-35 was sampled continuously at 5 cm-thick intervals from the base of the section to ~300 cm, and thereafter selectively to the top of the section. Ostracodes were restricted to a limited part of the section designated Unit E₁, while mollusks were found over a wider stratigraphic interval (Fig. 5).

The basal sediments in this section tentatively designated Units D-E (0 cm to 90 cm) and those assigned to Unit E₁ to ~120 cm contain no gastropods and rare ostracodes, indicating a wet-meadow environment. A similar environment typified upper Unit D and lower E at section LPM-34 (see previous discussion).

Mollusks from the two stratigraphic levels (1.4 and 2 m) that were collected indicate permanent water was present at both times. *Gyraulus circumstriatus*, *G. parvus*, as well as *Pisidium casertanum* are present in both horizons and require permanent water to survive. Terrestrial mollusks (e.g., *Pupilla muscorum*, *Vertigo berryi*) are also abundant at both levels, suggesting that standing water was not expansive and that moist banks were nearby.

The ostracode data is summarized with the stratigraphic profiles of four common species (Fig. 5). These species, but especially *Candona* n. sp., *Limnocythere paraornata*, and *Strandesia meadensis*, imply that the environment was dominated by flowing springs. The commonness of *Candona* n. sp. in these samples, as well as in the Unit E₁ in section OCI-11, provides a good example of the influence of regional climate over local hydrology. *Candona* n. sp. is a common species in springs at higher elevations in the region and north into central Nevada. It is rare to absent in the older record, so its abundance in these sediments implies climate change toward Holocene conditions. The ostracode assemblage from Unit E₁ in section OCI-11 also shows that flow dominated the environment. In the case of OCI-11, some of that flow appears to have been colder than is implied by the ostracodes in this section. The ostracodes at this section, with the exception of a single poorly preserved valve, are all surface-water

species, implying that extensive discharge of regional groundwater did not occur here. Thus, much of the water at this site is likely derived from the valley-fill aquifer. The sediments in the basal part of Unit E₁ contained a poorly preserved valve of *Limnocythere staplini*, an ostracode that lives in saline water with low alk/Ca solute ratios. That ostracode was probably not living at this site, but instead was blown to this site from the nearby playa.

Amargosa Desert section LWDD 6/8N

This section (LWDD 6/8N) was measured and sampled through one of the thickest portions of the diatomaceous mound located just off Highway 95 north of Lathrop Wells (Fig. 1), informally referred to as the Lathrop Wells Diatomites (Paces et al., 1996). The composite section measured >7 m thick (Fig. 6). These deposits have been the focus of intense geological scrutiny, due to their proximity to the proposed High-Level Nuclear Waste Repository ~20 km away at Yucca Mountain (e.g., Paces et al., 1996). Here we report only on the stratigraphy, ¹⁴C dating, and

ostracode paleontology of the deposits, with primary attention given to the youngest part of the section. Samples were obtained only in selected intervals, generally where mollusks or ostracodes were apparent in the field.

The lower 2.7 m (LWD 8N) of section exposed in a shallow trench cut is composed mainly of pale green (2.5Y 8/2d) to pale brown (10 YR 8/2d) pebbly to silty sand. The beds are mostly massive with almost no preserved bedding. Mollusks were found in two layers but dated only from the 170 cm level. Terrestrial and aquatic mollusks yielded a range of ages from $35,120 \pm 700$ (B-91923) to $41,910 \pm 1860$ ¹⁴C yr B.P. (B-90244) (Fig. 6; Table 1). As in the older deposits on Corn Creek Flat, we regard these as minimum ages.

The upper 5 m is exposed in one continuous section (LWD-station 6), and can be divided in three parts (Fig. 6). The lower 1.8 m consists of well-indurated greenish (5Y 7/2d) to white (10 YR 8/1d) sands and sandy loam. Volcanic pebbles and angular chips are dispersed throughout much of the unit, as are siliceous rhizoliths and carbonate nodules in the base. Several

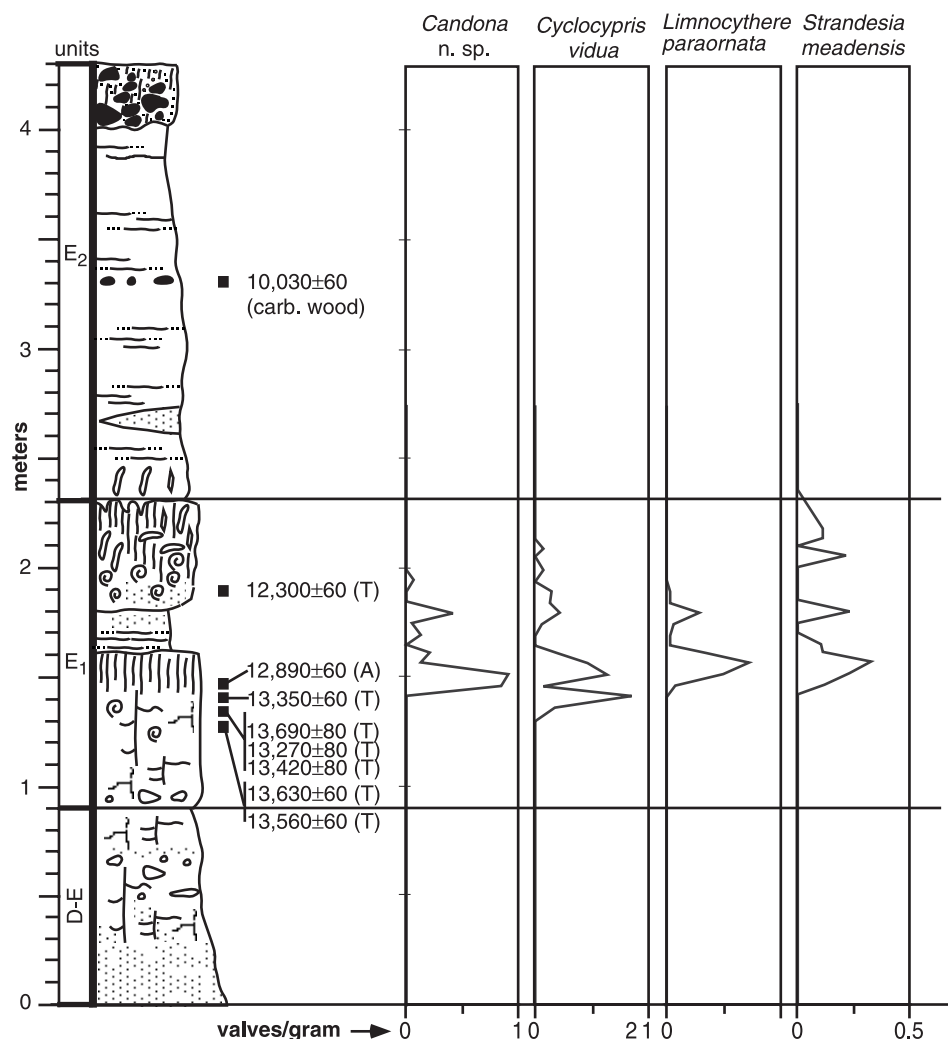


Figure 5. Stratigraphic section, units, and radiocarbon dates from LPM-35 west of Cactus Springs (115°48'03", 36°34'11"). See Figure 4 for explanation of lithologic symbols. A—aquatic mollusks, T—terrestrial mollusks.

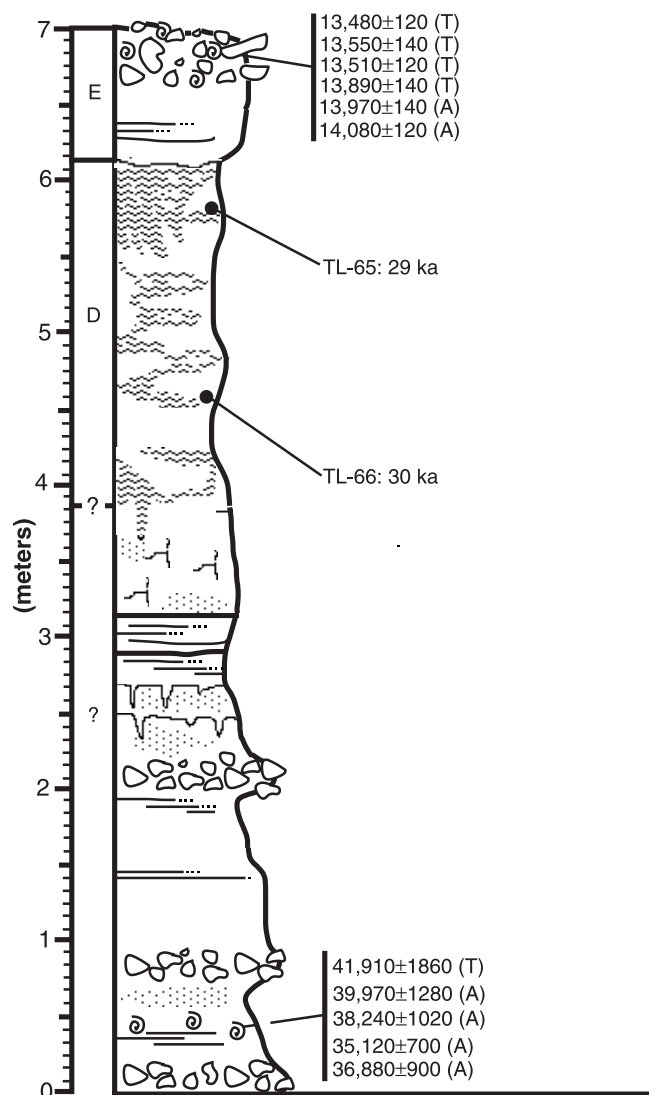


Figure 6. Stratigraphic section and dates from 6/8N at Lathrop Wells (116°35'14", 36°42'28"). See Figure 4 for explanation of lithologic symbols. A—aquatic mollusks, T—terrestrial mollusks.

vertically cracked partings cut the unit, suggesting hiatuses in deposition. No ^{14}C ages were obtained on this unit, which is devoid of mollusks; Paces et al. (1996) report U-series ages ranging from 186 ± 3 to 115 ± 3 ka.

A hard, white diatomite (whiter than 2.5Y 8/0d) extends from 2.2 to 4.15 m. It is largely noncalcareous, and contains dispersed pebbles of tuff. This unit contains a proboscidean tusk, as well as mammoth and horse tooth fragments. No radiocarbon-datable material was found, although Paces et al. (1996) report TL ages of 29 ± 11 and 30 ± 12 – 17 ka from this unit, and U-series ages of 42 ± 2 and 56 ± 6 ka on rhizoliths from the base of the diatomite.

The 5-m thick section is capped by 85 cm of very hard light orange to white marl. Dates from aquatic and terrestrial snails in the marl range from $13,480 \pm 120$ (B-83708) to $14,080 \pm 120$

^{14}C yr B.P. (B-83495) (Table 1). As such, the marl is assigned to Unit E₁. The same ages within Unit E also show up at Cactus Springs (Fig. 5).

This section was sampled opportunistically for whatever fauna was locally present. All of the ostracodes recovered from samples of this section suggest a complex array of spring discharge environments, much like those at the other sections. Ostracodes typical of flowing spring and seep environments dominate over wetland environments, consistent with the location of the site on an alluvial fan, rather than on the valley floor. The marl belonging to Unit E₁ (6.15–7 m) contains *Candona* n. sp. (consistent with Unit E₁ elsewhere), implying flow, but lacks taxa such as *Candona caudata* or the new genus/new species, implying high and/or cold flow. *Gyraulus circumstriatus* and *Pisidium* sp. from the marl indicate permanent water, but the additional presence of terrestrial gastropods (Succinidae, *Vertigo berryi*) is consistent with a low-flow spring to seep environment.

The diatomite (2.2–6.15 m) is dominated by *Denticula valida* according to J. Platt Bradbury in Paces et al. (1996). In the latter, Bradbury states:

This species characterizes warm (usually $<40^\circ\text{C}$), alkaline and slightly saline springs that are related to volcanic hydrothermal processes. For example, it occurs in springs on Mount Rainier, Washington, and in warm water habitats in Yellowstone National Park. However, it does not necessarily imply warm, hydrothermal water. For example, the species is abundant in shallow, near-shore water and marginal spring seeps at Black Lake (Adobe Valley, Mono County, California). Here the water is near ambient air temperature and saline as a result of evaporation. This species has a wide salinity tolerance ranging from ~ 1 ppt (parts per thousand) to ~ 15 ppt. The other diatoms at the LWD [species?] suggest that salinity was low, probably ~ 1 ppt.

Thus, this interpretation of the diatoms suggests discharge of deep, possibly warm, groundwater at the site.

STABLE ISOTOPE RESULTS AND INTERPRETATION

$\delta^{18}\text{O}$ results

The $\delta^{18}\text{O}$ data set is composed of >400 analyses on the valves/shells of ostracodes and mollusks that were collected from all of the study sections except LWDD 6/8N. The analyses include species that lived variously in flowing, standing, and groundwater. Land snails were also analyzed, but those and some of the aquatic mollusk data will be presented elsewhere (also see Sharpe et al., 1994).

The $\delta^{18}\text{O}$ (VSMOW) values from ostracode and mollusk species from all sections and all time periods (Figs. 7–8; Tables DR1–DR3¹) fall between about +16 and +22.2‰. In the largest data set from one location, section OCI-11, individual species show no clear clustering of $\delta^{18}\text{O}$ values according to habitat

¹GSA Data Repository item 2003070, Tables DR1–DR3, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/t2003.htm.

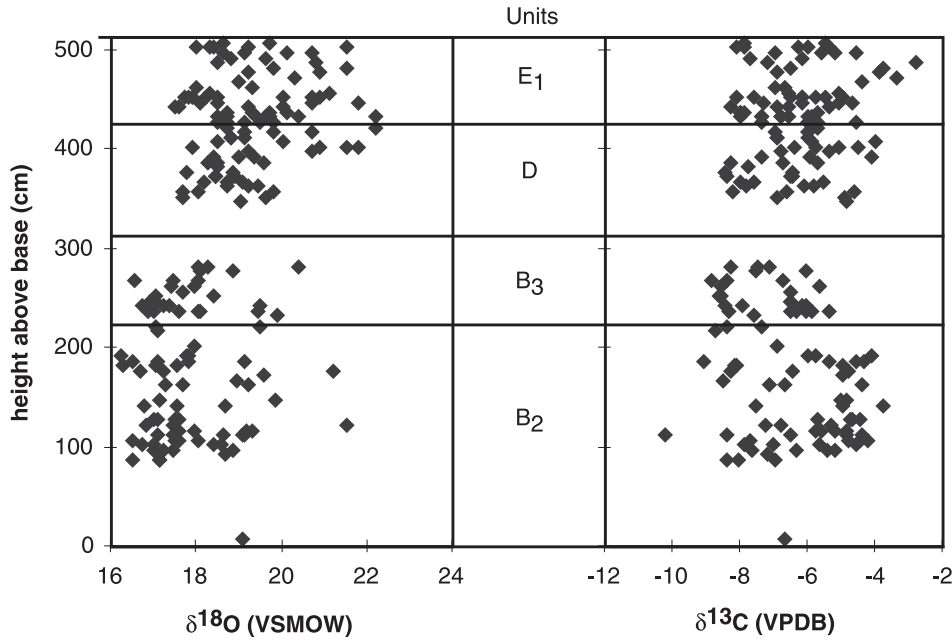


Figure 7. $\delta^{18}\text{O}$ (VSMOW) and $\delta^{13}\text{C}$ (VPDB) values of select ostracode taxa from OCI-11 on lower Corn Creek Flat.

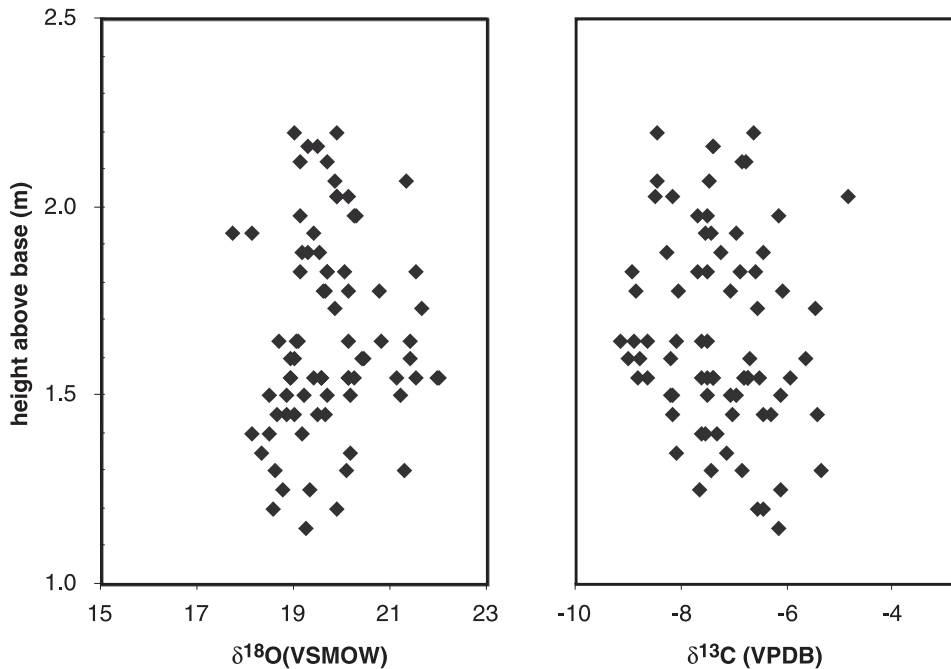


Figure 8. $\delta^{18}\text{O}$ (VSMOW) and $\delta^{13}\text{C}$ (VPDB) values of select ostracode and mollusk species from LPM-35 west of Cactus Springs.

preferences (Fig. 9A). For example, *Cypridopsis vidua*, a taxon with a wetland environmental preference, displays $\delta^{18}\text{O}$ values between +16.5 and +21.5‰ (n = 74) and *Candona rawsoni*, another wetland taxon, +17.3 to +22.0‰ (n = 36). Examples of flowing water taxa include *Candona caudata* (+16.7 to +22.2‰; n = 48) and *Strandesia meadensis* (+16.2 to +19.9‰; n = 19). Ostracodes that commonly live in and around the orifice of springs include *Candona accuminata* (+18.6 to +19.5‰; n = 4)

and perhaps a new genus/new species (+19.3 to +21.7‰; n = 9). *Limnocythere paraornata*, which probably lived in both flowing and standing water settings, returned $\delta^{18}\text{O}$ values of +16.3 to +21.5‰ (n = 74). Groundwater taxa also returned a broad spread of values, from +17.5 to +22.2‰ (n = 6).

$\delta^{13}\text{C}$ (VPDB) values for all taxa range between -9 and -3‰ for all but a few results from OCI-11 (Fig. 7), and between -9 and -5‰ for LPM-35 (Fig. 8).

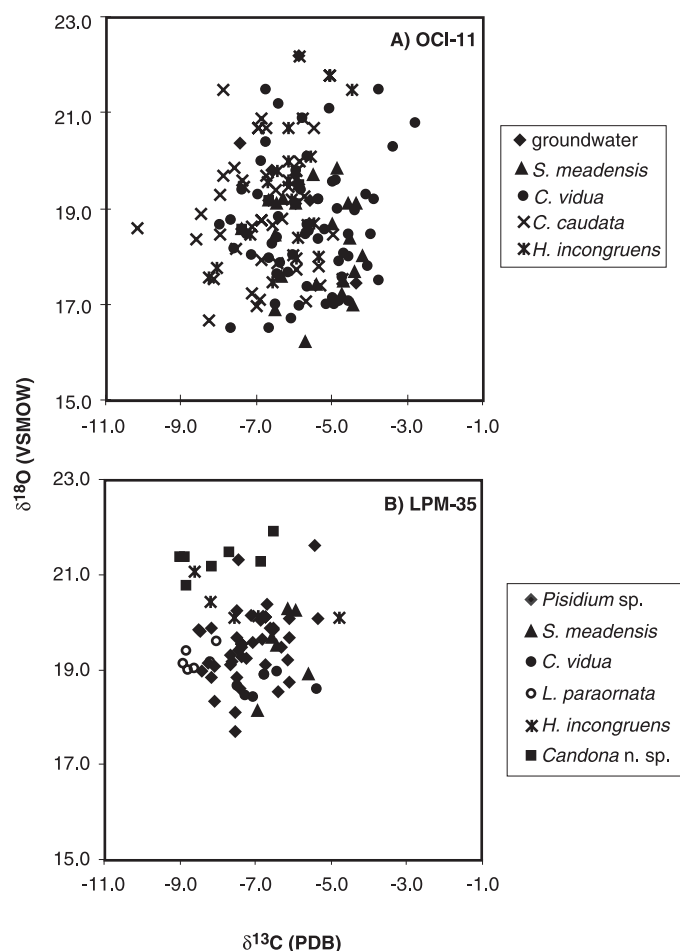


Figure 9. $\delta^{18}\text{O}$ (VSMOW) vs. $\delta^{13}\text{C}$ (PDB) of selected ostracodes. A: from OCI-11 on lower Corn Creek Flat. B: from LPM-35 west of Cactus Springs.

Interpretation

$\delta^{13}\text{C}$ values. The $\delta^{13}\text{C}$ value of ostracode shells is probably determined by the $\delta^{13}\text{C}$ value of dissolved inorganic carbon (DIC), with some possible influence by dietary carbon, following the analogy of aquatic clams (Dettman et al., 1999). Natural waters in the area have a pH between 7.5 and 8 (Thomas et al., 1991), and therefore the dominant inorganic carbon species in water is bicarbonate. DIC $\delta^{13}\text{C}$ values in groundwater are initially set by plant CO_2 at high elevations, which in the region is largely derived from C_3 plants ($\delta^{13}\text{C} = \sim -24\text{‰}$; Quade et al., 1989). Plant CO_2 with a $\delta^{13}\text{C}$ value of -24‰ would produce a DIC $\delta^{13}\text{C}$ value of $\sim -11\text{‰}$. However, reaction with limestone and dolostone along the flowpath should gradually increase the $\delta^{13}\text{C}$ value of DIC. This probably explains $\delta^{13}\text{C}$ values in springs in the area today, which vary from -10.9 to -7.8‰ (Table 2), and are higher at lower elevation. Average $\delta^{13}\text{C}$ values of DIC in the past were the same or slightly more negative (Quade et al., 1989). Calcite

formed from these waters should be 1.0‰ enriched in ^{13}C (Romanek et al., 1992), if in isotopic equilibrium, and thus be in the range -8.5 to -6‰ . This range in $\delta^{13}\text{C}$ values overlaps that displayed by most fossil ostracodes, suggesting that water DIC was the dominant source of carbon for shell building. Some $\delta^{13}\text{C}$ values in ostracodes are higher than -6‰ , particularly from OCI-11, implying a food source for some shell carbon, or locally high productivity environments (MacKenzie, 1985).

$\delta^{18}\text{O}$ values. $\delta^{18}\text{O}$ values from biogenic carbonates provide important insights into the nature of the paleoenvironments reconstructed from the ostracodes. They also provide constraints on paleotemperature maxima for spring water and air, and on other aspects of the paleohydrology.

Our $\delta^{18}\text{O}$ results show little discernible variation with depth in LPM-35, while there appears to be some small but probably significant variations in OCI-11. The overall lack of variation (Figs. 7–9) suggests that the hydrologic response in valley bottom environments to each major wet period, and even the later stages of the last wet period, was similar. Significant evaporation of streams and wetlands is also not in evidence. The similarity of mean $\delta^{18}\text{O}$ values from flowing and standing water taxa points to aquatic systems dominated by rapid through flow of water, and to water loss by overflow rather than evaporation.

$\delta^{18}\text{O}$ values in upper Unit D and Unit E display a modest ($1\text{--}2\text{‰}$) increase in mean values (Fig. 7). There are at least two possible explanations for this. The one favored by us is that this reflects an increase in the $\delta^{18}\text{O}$ value of meteoric water, as climate warmed during that late glacial period in recharge areas, thus shifting the $\delta^{18}\text{O}$ values of precipitation to higher values. Alternatively, some surface waters at this time may have experienced some evaporation prior to carbonate formation. However, the second explanation is inconsistent with the cold conditions implied by the ostracode taxa present, as discussed in a previous section.

Our extensive $\delta^{18}\text{O}$ results provide a unique opportunity to reconstruct paleotemperatures for periods represented by our sections. To do this we must first constrain the variables that determine the $\delta^{18}\text{O}$ value of associated carbonates in most aquatic settings. Other than temperature, these variables include the $\delta^{18}\text{O}$ value of host water and the degree of attainment of temperature-controlled isotopic equilibrium during carbonate formation. In this section of the paper we will examine each of these variables in the wetlands and spring context. This analysis in turn provides some constraints of mean annual air temperature (MAT) in the region during the same periods.

Attainment of isotopic equilibrium. Some biologically precipitated calcites do not attain isotopic equilibrium with waters in which they form. Such “vital effects” may account for some of the range in $\delta^{18}\text{O}$ values from various ostracodes from the same stratigraphic level. Xia et al. (1997) showed that *Candona rawsoni* exhibits a $0.8\text{--}1.0\text{‰}$ enrichment over equilibrium $\delta^{18}\text{O}$ values. Similarly, results from Bacon (1999) seem to suggest that some ostracodes (crawlers) make a shell with isotope values higher than for inorganic calcite in equilibrium with the same water. Conversely, other ostracodes (swimmers) make a shell that

TABLE 2. SPRING ELEVATIONS, TEMPERATURES, AND ISOTOPIC COMPOSITIONS FROM THE SPRING AND SHEEP RANGES AND INTERVENING VALLEYS

Spring name	Spring elevation (m)	Spring temperature (°C)	$\delta^{18}\text{O}$ (VSMOW)	$\delta^{13}\text{C}$ (VPDB)
Peak Creek	3260	NA	-12.9 to -13.8	-9.5
Cave Creek	3048	5	-13.3	NA
Two Spring	3048	4	NA	NA
Lee Canyon Ski Spring	2967	7.7	-13.6	-9
Deer Creek #1	2870	4.3	-14 to -14.1	-8.2 to -8.5
West Spring	2804	5.5	NA	NA
Upper Macks Canyon	2710	9.2	NA	-9.1
Clark Spring	2648	10.4	-12.9	-8.6
Deer Creek #2	2646	7.8	-13.4	-9.6
Trough	2505	13.2	-14.1	-10.9
Lower Stanley B	2461	10	NA	NA
Trout Spring	2360	7.5 (6.9–8.5)	-12.9 to -14.1	-8.2
Fletcher Spring	2350	8.4	NA	NA
Fletcher Spring	2310	11.5	NA	NA
Mud	2280	11	-14.1	-8.7
Buck	2224	13.9	-13.6	-9.4
Cold Creek	1930	10 (9.5–12)	-13.3 to -14.2	-9.3
Willow Spring	1826	10.5	-13.4	-9.6
Harris Spring	1820	14	-13.7	-8.5
Wood Canyon Spring	1780	17.4	NA	NA
East House Spring	1620	18.9	NA	NA
Grassy Spring	1570	19.4	NA	NA
Grapevine Spring	1490	26.5	NA	NA
Cactus	987	20.6	NA	NA
Indian	969	26	-13.0 to -14.2	-7.8
Paiute Indian Reservation Well	927	18.7	-14	-8.7
Pahrump Spring Well	823	25	-13.6	-7.6
Corn Creek Spring	817	21	-12.9 to -13.0	-8.3
Tule Spring Park	750	21	NA	NA

Note: data from McKinley et al., 1991; Thomas et al., 1991; Winograd et al., 1998; and this study.

is in isotopic equilibrium or nearly in equilibrium with host water (Bacon, 1999). Vital effects therefore may account for the slightly lower $\delta^{18}\text{O}$ values among, for example, *Cypridopsis vidua* (aver. 18.6), a swimmer, compared to *Candona caudata* (aver. 19.1), a crawler (Fig. 9A). In our paleotemperature estimates, we use the isotopic results both from groundwater candonids, and assume 1.0‰ vital effect, and from *C. vidua*, for which we assume no vital effects during valve formation. It must be kept in mind, however, that neither the groundwater candonids nor *C. vidua* have been studied for vital effects in controlled laboratory settings.

$\delta^{18}\text{O}$ value of paleowaters. Study of the paleo-spring and wetland deposits in the valley bottoms shows them to be groundwater fed, with no evidence of any perennial flow from the surrounding fans. $\delta^{18}\text{O}$ value of standing and flowing water in valley wetlands is determined by the $\delta^{18}\text{O}$ value of meteoric water

($\delta^{18}\text{O}_{\text{mw}}$) feeding the groundwater system, and by the extent of subsequent evaporation. For the Corn Creek and Cactus Springs areas, the main recharge zones are the high peaks of the Spring Range; the rugged Sheep Range serves as an important additional source to the east side of Corn Creek Flat (Fig. 1). Most major springs in these mountains have been sampled, providing a detailed picture of the patterns of recharge. The $\delta^{18}\text{O}_{\text{mw}}$ values of these springs fall in a narrow range between -12.9 and -14.3‰ (Table 2). Winograd et al. (1998) demonstrated that this narrow isotopic range reflects the dominance of winter recharge (~90%) at all elevations, even though ~40% of precipitation falls in summer. Importantly, these values show up in valley-bottom springs fed by the deeper carbonate aquifer, and in much smaller mountain springs flowing along variable but often very short flow paths (Table 2). The abundance of groundwater (carbonate aquifer)

taxa in some strata, but absence in others, suggests that both types of springs (long- and short-flow path) may have discharged into valley bottoms in the past.

Recharge from the Spring Mountains also flows through Devils Hole, where vein calcite deposits record fluctuations in the $\delta^{18}\text{O}_{\text{mw}}$ of groundwater over the past 500,000 yr (Winograd et al., 1992). Calcite formed at Devils Hole during glacial periods has $\delta^{18}\text{O}$ values that are 1.2–2.2‰ lower than interglacial-age calcite, with the smallest difference, 1.2‰, associated with the last deglaciation (Marine Isotope Stages I to II) (I.J. Winograd, 2000, personal commun.). These differences are thought to be caused mainly by colder conditions during glacial periods in recharge areas high in the Spring Mountains (Winograd et al., 1992). A variety of evidence presented by Winograd et al. (1992, 1997) and Thomas (1996) argues for very short (no more than a few thousand years) transit times in the carbonate aquifer from recharge areas, even though ^{14}C dates on associated groundwater yield apparent late-Pleistocene ages. Compared to Devils Hole, our study sites at Cactus Springs and Corn Creek are less than half the distance to recharge areas, and at least partly fed by the same carbonate aquifer. The vein calcite at Devils Hole therefore provides well-constrained $\delta^{18}\text{O}$ values for waters discharging in our valley bottom sites during glacial periods. For our paleotemperature estimates we assumed a $\delta^{18}\text{O}_{\text{mw}}$ value of -13.0‰ for Holocene-age groundwater. This assumption makes our paleotemperature estimates maxima, although we agree with Winograd et al. (1998) that the weighted average $\delta^{18}\text{O}_{\text{mw}}$ values ($= -13.5\text{‰}$) of three large-flow springs in the Spring Mountains is probably more representative of Holocene recharge. Using 1.2‰ for the glacial/interglacial shift in $\delta^{18}\text{O}_{\text{mw}}$ values, we estimate a $\delta^{18}\text{O}_{\text{mw}}$ value for glacial periods to be -14.2‰ . Use of a 2.2‰ shift would render our paleotemperature estimates even colder.

The other important variable influencing the isotopic composition of paleo-waters is evaporation. The extent of evaporation can be quite variable, and depends on residence times of water, air and water temperature, windiness, and other factors. In many lakes, particularly in dry settings, evaporation is often by far the most important determinant of host water $\delta^{18}\text{O}$ values, so much so that in many lake studies the $\delta^{18}\text{O}$ value of carbonates is viewed as a proxy for evaporation-controlled lake volume.

In our paleo-spring systems, the situation is simpler than in most lakes, and appears to involve little or no evaporation. This feature of the spring/wetland system is not surprising given their physical character. At Corn Creek Flat, a shallow marsh, probably no more than a few meters deep, developed in Units B₂, B₃, and D time behind a shallow impoundment formed by encroachment of alluvial fans from both sides of the valley (Quade, 1986). The marsh deposits grade down valley into alluvial channel deposits containing abundant perennial water fauna, showing that the small marsh overflowed continuously through the narrows between the fans. This would have greatly reduced residence times of water in the marsh, and explains the total lack of primary salts in the deposits. In the case of the deposits at Cactus Springs and Lathrop Wells, there is no major topographic closure to

impound discharge; springs waters must have flowed as “freeface” discharge (Quade et al., 1995), and ponded only locally (Quade and Pratt, 1989).

These inferences of short residence times for paleo-water are also strongly supported by isotopic evidence from both of the Corn Creek sections and the Cactus Springs section. The similarity in the means of $\delta^{18}\text{O}$ values between standing and flowing water taxa argues against large differences in average temperature between flowing and standing water, and for short residence times and little evaporation.

Estimates of water temperatures and mean annual temperatures. The $\delta^{18}\text{O}$ values of fossil ostracodes from our sections can provide constraints on *maximum* mean annual temperatures in the past, provided the list of assumptions discussed above is satisfied. For our paleotemperature reconstruction, we selected results from two types of ostracodes: groundwater candonids and *Cypridopsis vidua*. The advantages of using groundwater taxa are that (1) they grew within the groundwater, thus eliminating any possible influence of postdischarge evaporation on the $\delta^{18}\text{O}$ values, and (2) they would have grown at the same temperature as that of local spring water, temperatures that in turn relate to mean annual temperatures, as will be discussed below. The disadvantages of using the groundwater taxa are that (1) as candonids, they are probably subject to vital effects like their relative *C. rawsoni*, and (2) they are not common at all stratigraphic levels. The lowest $\delta^{18}\text{O}$ value ($n = 15$) among groundwater taxa in Unit D from OCI-11 and LPM-34 is $+16.9\text{‰}$, the value we adopt in our calculations below, thus ensuring that our paleotemperature estimates discussed are *maxima*. Too few analyses of groundwater taxa ($n = 4$) are available from Unit B for our analysis. Most $\delta^{18}\text{O}$ values from both ostracodes (spring and wetland) and aquatic clams are higher than 17‰ . Use of the many higher $\delta^{18}\text{O}$ values would produce much colder paleotemperature estimates.

We use the following values, drawn from previous discussion, for reconstruction of paleo-water temperatures (T_{watermax}) from groundwater candonids at the point of discharge: $\delta^{18}\text{O}_{\text{mw}}$ (VSMOW) $= -14.2$ and $\delta^{18}\text{O}_{\text{calcite}} = +16.9\text{‰}$ (VSMOW). Nearly all ostracode valves are composed of low-Mg calcite. The temperature control on fractionation for ^{18}O and ^{16}O between calcite and host water is (Kim and O’Neil, 1997):

$$1000\ln\alpha_{\text{calcite-water}} = (18.03 \times 10^3/T) - 32.42$$

where T is absolute temperature, and $\alpha_{\text{calcite-water}}$ is the calcite-water fractionation factor. These constraints produce an estimate of T_{watermax} of $+10.9\text{ °C}$ (Fig. 10) for Unit D. T_{watermax} increases to $\sim 15\text{ °C}$ using a $+0.8$ to $+1\text{‰}$ vital effect (Xia et al., 1997).

We can take a similar approach to paleotemperature reconstruction using other ostracode taxa. Our other choice is *C. vidua* because it is a swimmer, and therefore apparently not subject to vital effects (Bacon, 1999), and because we have >85 analyses spanning several time periods from several sections. We selected the lowest $\delta^{18}\text{O}$ values of *C. vidua* from each stratigraphic horizon, thereby making our paleotemperature estimates

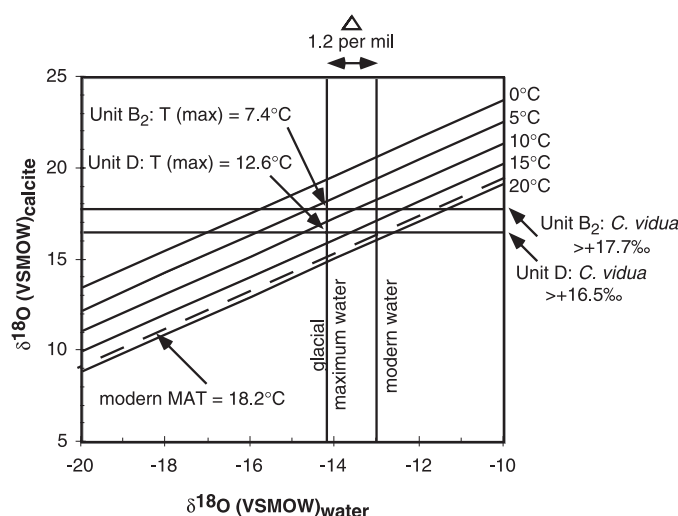


Figure 10. Graphical depiction of paleo-water temperature reconstruction using the limiting $\delta^{18}\text{O}$ (VSMOW) value from fossil ostracodes (*Cypridopsis vidua* only) of +16.5‰ for Unit D and B₃, +17.7‰ for Unit B₂, and assuming no vital effects during calcite shell growth. Lines represent predicted $\delta^{18}\text{O}$ (VSMOW) values of calcite in isotopic equilibrium with local spring water, using fractionation factors from 0 to 20 °C from Kim and O'Neil (1997). Constraints on the $\delta^{18}\text{O}$ (VSMOW) value of modern water are provided by Thomas et al. (1991), Winograd et al. (1998), and unpublished data of the authors, and for glacial-age water, by Winograd et al. (1992, 1997; 2000, personal commun.).

maxima, as well as minimizing any potential effects of evaporation. We adopt the following $\delta^{18}\text{O}$ values in our calculations below: +17.7‰ from Unit B₂ (OCI-11 only, $n = 40$), +16.5 for Unit B₃ (OCI-11 only, $n = 7$), and +16.5 from Unit D (OCI-11 and LPM-34, $n = 30$) (Fig. 10). Most $\delta^{18}\text{O}$ values from both ostracodes (spring and wetland) and aquatic clams are higher than 17‰. Use of the many higher $\delta^{18}\text{O}$ values would produce much colder paleotemperature estimates. Based on previous discussion, we assume $\delta^{18}\text{O}_{\text{mw}}$ (VSMOW) = -14.2‰ to reconstruct paleo-water temperatures (T_{watermax}) at the point of discharge. Using these constraints and the same equation as above from Kim and O'Neil (1997), we obtain an estimate of T_{watermax} of +7.4 °C for Unit B₂, and +12.7 °C for both Unit B₃ and Unit D (Fig. 10), assuming no vital effects.

Two key issues surrounding the use of *C. vidua* are (1) post-discharge evaporation of waters could have occurred, and (2) many could and probably did live far from the discharge point, in places where spring water temperature may have shifted in the direction of air temperature. As for evaporation, we have already argued that this should have been minimal in this hydrologic system, and we selected the lowest $\delta^{18}\text{O}$ values to minimize any effects. As to temperature, *C. vidua* very likely built its valves in the summer half-year when air temperature exceeds mean annual temperature. Thus, use of $\delta^{18}\text{O}$ values from *C. vidua* should produce overestimates (*maxima*) of paleo-mean annual temperature.

Paleo-spring temperature calculated above provides constraints on mean annual air temperature (MAT) in the past, through the relation of spring and air temperature in the study area today. For MAT today, we used a linear regression of data from Kyle Canyon Ranger Station (2225 m) and Las Vegas (640 m). Data compiled for 28 springs in the Spring and Sheep Range shows that spring temperature generally increases with decreasing elevation (Fig. 11; Table 2). Only a few springs have seasonal data, which shows up to 3 °C annual variation, coldest in the early spring, and warmest in the late summer and fall (Winograd et al., 1998). The small amplitude results from the buffering effect on water temperature by bedrock. For this reason, annually averaged spring temperatures are generally close to mean annual air temperatures, at least for short-flow path springs (Mifflin, 1968). Our own plot of springs in nearby ranges shows that spring temperatures are similar to or higher than local MAT (Fig. 11). The difference between the two generally increases at lower elevation. This is to be expected, because water discharging in valleys will have traveled the furthest, and in the simplest case for most groundwaters, circulated the deepest. For these reasons, we view our estimates of paleo-water temperatures as maxima for local mean annual air temperature. Local MAT today is 18.2 °C at Corn Creek. Using the $\delta^{18}\text{O}_{\text{mw}}$ values from *C. vidua*, this implies that MAT was a *minimum* of 10.8 °C cooler during Unit B₂ deposition, and 5.6 °C cooler during Unit B₃ and Unit D deposition. If Unit B₂ proves to be correlative with Isotope Stage 6 at Devils Hole, then the large glacial-interglacial shift in $\delta^{18}\text{O}_{\text{mw}}$ of 2.2‰ for that transition produces an estimate of minimum cooling of 15.2 °C. Using $\delta^{18}\text{O}_{\text{mw}}$ values from groundwater canidons, MAT during Unit D deposition was a *minimum* of 2.9 °C colder than today, assuming a 1.0‰ vital effect.

We did not attempt a paleotemperature estimate for Unit E because of uncertainty over the value of $\delta^{18}\text{O}_{\text{mw}}$ during the late glacial period. At both OCI-11 and LPM-35, the average $\delta^{18}\text{O}$ value of ostracodes from uppermost Unit D and Unit E₁ (+18.7 ± 1.6; $n = 64$) is ~1‰ higher than for ostracodes in lower/middle Unit D levels (+17.6 ± 1.0; $n = 53$). We attribute this rise to probable increases in the $\delta^{18}\text{O}_{\text{mw}}$ value of local springs in this transition period from glacial to interglacial conditions. The full extent of this glacial-to-interglacial shift is 1.2‰, as previously noted. The exact composition of water discharging ca. 13–12 ka is hard to constrain. We will await documentation of calcite records from Devils Hole spanning the last 50 ka before attempting any late glacial temperature reconstructions.

Our paleotemperature estimates are in line with most other estimates from the southern Great Basin for glacial maxima. Roberts et al. (1997) estimated that paleotemperatures were 10–15 °C colder than today for the period 120–186 ka, using fluid inclusion homogenization temperatures in salts from Death Valley. This compares to our own estimate of at least 10.8 °C colder during Unit B₂ deposition. Dohrenwend (1984), using the distribution of paleo-nivation features with elevation in the Great Basin, estimated temperature changes of ~7 °C since the LGM. Spaulding (1984) and Thompson et al. (1999) relied on several

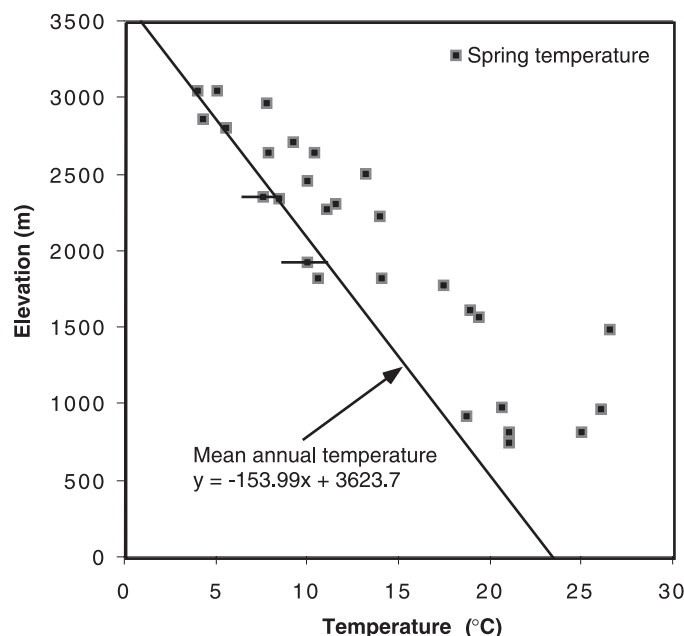


Figure 11. Mean annual air temperature and spring water temperature (using data from McKinley et al., 1991; Thomas et al., 1991) as a function of elevation for the Spring Mountains. A few springs have seasonal temperature data, also shown. This seasonal variation is $\leq 3^\circ\text{C}$ in springs at higher elevation, and negligible in low-elevation springs.

lines of evidence from fossil packrat middens for their estimates and arrived at changes of $\sim 5.5\text{--}7^\circ\text{C}$ since the LGM. These estimates rely largely on climate reconstructions for conifers that exhibit down-elevation displacement of $\sim 1000\text{ m}$ during the LGM, and on the absence of thermophilous shrubs such as creosote (*Larrea divaricata*) in the area of Yucca Mountain. The same studies call for paleotemperatures in the late glacial (post-12 ^{14}C ka) only $0\text{--}4^\circ\text{C}$ colder than today, coincident with the summer insolation maximum in the northern hemisphere. Unfortunately, we have no isotopic results nor constraints on the $\delta^{18}\text{O}$ value of paleo-water from that period (Unit E₂) upon which to base our own estimates of paleotemperature.

Several estimates of paleotemperature during the LGM center around the temperature changes required to restore pluvial lakes, mostly from the central and northern Great Basin. Estimated temperature changes since the LGM are generally $<6^\circ\text{C}$ (e.g., Snyder and Langbein, 1962; Mifflin and Wheat, 1979). A good review of these estimates appears in Mifflin and Wheat (1979).

Finally, Benson and Klieforth (1989) derived paleotemperature estimates for the region based on the difference between the $\delta^{18}\text{O}$ value of modern and inferred full-glacial groundwater. This analysis assumed that changes in equatorial temperature since the LGM were small, and that ^{14}C dates on groundwater required no large correction. Evidence developed since 1992 (Winograd et al., 1992; Thomas, 1996; Stute et al., 1995) suggests that neither

assumption is warranted, and thus we do not consider Benson's estimates further here.

SYNTHESIS OF CLIMATIC RECORDS IN THE REGION

The oldest spring deposits in our study sections belong to Unit B₂. These represent a large spring discharge event that flooded not only the bottom of Corn Creek Flat but portions of the Tule Springs area, and perhaps the spring cluster at the Lathrop Wells Diatomite. Amino acid ratios of mollusks collected from Unit B₂ in a previous study (Quade et al., 1995) are similar to those in deposits representing the second oldest major spring discharge event in the Pahrump Valley, west of the Spring Mountains. Unfortunately, we have no absolute age control on Unit B₂, other than the dates of $>41\text{ }^{14}\text{C}$ ka obtained in this study. For reasons discussed above, we regard these ages as infinite. A well-developed paleosol is preserved in some places (but not at OCI-11, where it was apparently eroded) on the top of Unit B₂ and below Unit D, demonstrating substantial age separation ($>10^4\text{ yr}$) between them. For this reason, we tentatively correlate Unit B₂ with the penultimate deep-lake episode in Death Valley (ca. 140 and ca. 190 ka; Ku et al., 1998; Lowenstein et al., 1999), and isotope Stage 6 at Devils Hole (186 to $>130\text{ ka}$; Winograd et al., 1992, 1997) and in the deep sea record (Imbrie et al., 1984). The wetlands of Unit B₂ are more extensive than Unit D at Corn Creek, but apparently less so than Unit D near Tule Springs (Haynes, 1967).

The types of ostracodes present during Unit B₂ time, combined with their shell $\delta^{18}\text{O}$ values, point to a climate much colder than today's, as well as that of the LGM (Unit D). Whereas the climate was very cold, the wetlands associated with Unit B₂ were also ephemeral. However, the $\delta^{18}\text{O}$ values from ostracodes in Unit B₂ do not show patterns of enrichment in ^{18}O indicative of evaporation of the waters. We suggest that periodic drying was caused by drops in the water table below the land surface rather than by evaporation, probably in the presence of a climate with cold, relatively dry winters, and cool summers with frontal-storm derived rainfall. This climate is somewhat analogous to that in the modern-day northern prairies of Canada. The continental ice sheet associated with isotope Stage 6 was very large, potentially displacing polar air masses much further south than in other glacial periods. As such, the cold dry arctic high pressure cells might have resided in southern Nevada during the winters of this period, whereas the polar lows would move northward to southern Nevada in the summers, much as both air masses do today in the northern prairies of Canada. This sort of climate is also consistent with the very large lake believed to have existed in Death Valley (Lowenstein et al., 1999), which would require a substantial reduction in air-temperature.

Unit D was deposited during the period of highest effective moisture in the last 30 ka, based on our evidence from Corn Creek Flat, Tule Spring, and perhaps at Lathrop Wells. Only the Corn Creek Flat sections contain well-dated evidence of this

<26.3–16.4 ^{14}C ka wet event. Dates falling in the period 16.4–14.5 ^{14}C ka are not known from any section that we have studied. This negative evidence suggests but does not prove that this was a relatively dry period.

Ostracodes show that paleo-wetlands associated with Unit D had greater permanence than those in Unit B₂, in settings that included flowing springs in addition to streams or perhaps instead of streams. The types of ostracodes in Unit D also imply greater summer temperatures than during the deposition of Unit B₂. Collectively, those conditions suggest a warmer and wetter climate compared to that of Unit B₂, perhaps consistent with atmospheric circulation associated with a smaller continental glaciation. During this time, the winter season may have been the wet season, with snow common at high and perhaps low elevation, whereas the summer season would have been relatively warm, but not hot like today, and dry. Such a climate is also consistent with the much smaller lakes in Death Valley discussed below, because a generally warmer climate with warm dry summers would be less likely to sustain large lakes. Wet-meadow environments appear to be common late in the deposition of Unit D and as with upper Unit B₂, possibly indicating climate change toward a warmer and drier climate.

The wet phase between 14.5 and 12.3 ^{14}C ka is well represented in several sections, including Corn Creek (OCI-11; previously published sections in Quade et al., 1995, and Brennan and Quade, 1997), the Tule Springs archeological site (Haynes, 1967), Cactus Springs (LPM-35), and at Lathrop Wells (LWD-6/8N). To this we can add new dates from Unit E₁ channels from Corn Creek Flat (Table 1, sections 186/187; Figure 12). This phase ended shortly after 12.3 ^{14}C ka, as indicated at LPM-35 at Cactus Springs, where no further discharge is recorded higher in the section. LPM-35 at Cactus Springs stands ~60 m above the current

water table, and therefore probably records only the largest paleo-recharge events capable of producing that much rise in the water table. Taken together, this evidence suggests that the wet phase between 14.5 and 12.3 ^{14}C ka was the wettest post-Unit D period in the region, wetter than the period 11.6–9.8 ^{14}C ka when black mats formed all over the area (Quade et al., 1998).

This same chronology of paleohydrologic changes has been documented, although usually in less detail, in several lake and one other spring record from the region. The most robust records are those that involve U-series dating, because of the uncertainties surrounding reservoir corrections for ^{14}C dating. The chronology of lake fluctuations at Lake Manly in Death Valley and, to some extent Searles Lake, agree with our own. Paleo-Lake Manly was a saline but perennial lake between ca. 26 and 8.7 ^{14}C ka (30.1 ± 3.3 to 9.6 ± 3.3 cal. yr from U-series total-dissolution ages on cored halites) and attained its late Pleistocene highstand ca. 21–15.0 ^{14}C ka (24.7 ± 0.9 to 18 ± 1.6 cal. yr from U-series dates on shoreline tufas; Ku et al., 1998; Lowenstein et al., 1999). These dates overlap with the age range of Units D and E.

A U-series date on salt layer S-7 at Searles Lake further constrains the beginning of the same wet episode (called the “Parting Mud” in the core) to shortly after 23.7 ± 1.5 (calendar years) (Phillips et al., 1994). Curiously, dates from shoreline tufas at Searles Lake thought to be equivalent to the Parting Mud are no older than ca. 14 ^{14}C ka (Lin et al., 1997). U/Th dates from the tufas fall between 14.5 and 13.5 ka, while ^{14}C dates are ~1000 yr younger. This discrepancy remains unexplained. As it stands, the high shoreline in Searles Lake appears to correlate with Unit E₁, not D.

Extensive U-series dating of spring calcite in Browns Room constrains periods of higher water tables in the Devils Hole system to between 42–35.5 (44–38.3 cal. yr) and 25.5–17.6 (30–19.6 cal. yr) ^{14}C yr B.P. (Szabo et al., 1994). The

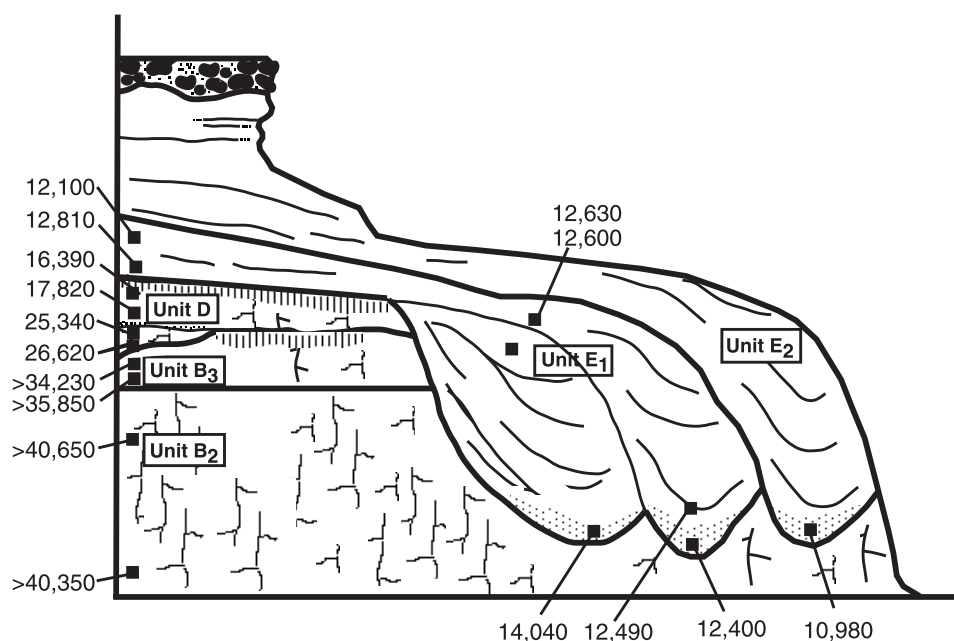


Figure 12. Composite stratigraphy of lower Corn Creek Flat, based on results from OCI-11, LPM-34, sections 186 and 187 (Table 1), and previous work.

older high-water episode partially overlaps the age of Unit B₃. The younger episode correlates almost perfectly with our estimated ages for Unit D. The water table was in decline but still higher than today's levels between 14.2 and 6 (17–6.8 cal. yr ¹⁴C yr B.P., correlative with Unit E.

The Silver Lake chronology is based on ¹⁴C dates on both charcoal and lacustrine organic matter (Wells et al., 1989; Enzel et al., 1989; Wells et al., this volume), shells and tufa (Wells et al., 1987), and shells (Ore and Warren, 1971; Wells et al., 1989; Wells et al., this volume). The agreement of the charcoal dates with the other dates suggests that ¹⁴C reservoir effects are minimal. Wells et al. (1989) places the termination of the earliest continuous high lake phase (Mojave Lake I) at ca. 16.5 ¹⁴C ka, exactly the age we estimate for the end of Unit D deposition. Between 16.5 and ca. 13.7 ¹⁴C ka, the lake is intermittent (Intermittent Lake II), then reverts to another continuously high lake condition between 13.7 and 11.3 ¹⁴C ka (Mojave Lake II). This overlaps with the period of high discharge represented by Unit E₁ (14–12.3 ¹⁴C ka). The lake then passes through a period of intermittent highstands (Intermittent Lake III) between 11.3 and 8.7 ¹⁴C ka, almost exactly correlative with the modest resurgence in discharge represented by Unit E₂.

The paleoclimate record for Owens Lake is one of the most detailed in the region (e.g., Smith and Bischoff, 1997; Menking et al., 1997; Benson et al., 1996, 1997). However, it is premature to compare our records to that of Owens Lake until the chronology of Owens Lake is fully developed. At this point, at least two ¹⁴C-based chronologies have been presented (Benson et al., 1996, 1997; Bischoff et al., 1997), but until there is consensus on the extent of the ¹⁴C reservoir effect, we will refrain from comparison to our record.

Evidence from fossil packrat middens in the region and from glacial deposits in the Sierra Nevada provides further support for our chronology from spring deposits. Middens from the region contain very cold-tolerant vegetation during the LGM up until 16.5 ¹⁴C ka. Glaciers on the nearby eastern slopes of the Sierra Nevada underwent several major expansions at the same time as Unit D deposition, termed the Tioga 2 (22 ± 1.5 ¹⁴C ka) and 3 (16.5 ± 1.5 ¹⁴C ka) advances, dated by ³⁶Cl (Phillips et al., 1996). After this time, thermophilous vegetation begins its slow movement both into the region and upwards in elevation. This date marks the drying of Unit D wetlands in our valley bottom records, and thus we take the change in vegetation also as a response to reduction in effective moisture. This reduction in effective moisture is also reflected in major contraction of Sierran glaciers prior to 14.5 ¹⁴C ka. A brief readvance between ca. 14.5 and 13 ¹⁴C ka (Tioga 4) correlates with the increase in discharge associated with Unit E₁, an event not remarked upon in the midden record. Unit E₂ (11.6 to ≤8 ¹⁴C ka) time is characterized in the midden record by vegetation typical of moister and perhaps cooler conditions than today, particularly at lower elevations (Spaulding, 1995). No Sierran glacial advances are dated from this period; if present, they would be small advances below the headwall cirques.

CONCLUSIONS

Detailed analysis of four new stratigraphic sections in southern Nevada provides a wealth of paleoclimatic information on the last two glacial periods. Carbon-14 dates on land snails provide the geochronological framework for these deposits, augmented by a few dates on organic matter. The penultimate glacial period is probably represented by the pale green muds of Unit B₂. During this and the last glacial period, spring discharge supported extensive, but at times ephemeral, wet meadows, streams, and wetlands. These environments hosted a diverse assemblage of spring and wetland ostracodes and mollusks, as well as highly endemic ostracodes that lived in the groundwater. The types of ostracodes present, as well as isotopic evidence, point to colder conditions than during the LGM (Unit D). Unit B₂ is likely contemporaneous with the penultimate deep-lake episode in Death Valley (Lake Manly, Blackwelder Stand: ca. 140 and ca. 190 ka) and at Owens Lake (118–140 to >155 ka) and with isotope Stage 6 at Devils Hole (186 to >130 ka) and in the deep sea record.

Carbon-14 dates on land snails provide the first firm control on the age of Unit D in the region, and show that it spans much of the period <26.3–16.4 ¹⁴C ka. As during Unit B₂ time, an extensive marsh covered the Tule Springs area, while Unit D on Corn Creek Flat is represented by both channel and marsh sediments. Evidence from ostracodes suggests that wetlands were more permanent during Unit D than Unit B₂ time. Unit D appears to be present as diatomites in localized spring deposits near Lathrop Wells. Unit D correlates with period of high lake–groundwater stands at Brown's Room (Devils Hole), Silver Lake and Lake Manly (Death Valley), and with glacial advances Tioga 2–3 in the eastern Sierra.

Unit E (14.5 to ca. 7.2 ¹⁴C ka) is present at Corn Creek Flat, Cactus Springs, and in a marl above diatomites (Unit D?) near Lathrop Wells. Ostracodes from Unit E are similar to those of Unit D on Corn Creek Flat, except that wetland taxa are less abundant, and groundwater taxa are not present in the Cactus Spring section. Moderate highstands during this time are also evident in the Silver Lake record, and in an apparent highstand at Searles Lake as well as the Tioga 4 glacial advance. Comparison with the Owens Lake record awaits development of a firm geochronological framework for the cores. Deposition in Unit E₁ appears to represent largely a mix of cold-flowing springs and streams.

Over 400 isotopic analyses of ostracodes and mollusks from Units B₂, D and E yield $\delta^{18}\text{O}$ values ranging between +16 and +22.2‰. Mean $\delta^{18}\text{O}$ values for standing and flowing water are similar, suggesting that the water was lost from the wetlands and streams by overflow from the basin rather than by evaporation. In general, mean $\delta^{18}\text{O}$ values of all ostracodes in Units B and D are similar, while those from Unit E are slightly higher, perhaps the result of late glacial increases in air temperature in recharge areas. The $\delta^{18}\text{O}$ results from ostracodes provide a unique opportunity to constrain paleotemperatures in valleys during wet periods. Evidence from modern springs in the area and from nearby Devils Hole suggest that $\delta^{18}\text{O}$ values of paleo-waters during wet

periods were no higher than -14.2‰ . This and $\delta^{18}\text{O}$ values of $+16.5$ to $+17.7\text{‰}$ from *C. vidua* produce an estimated maximum paleotemperature for springs of $7.4\text{ }^{\circ}\text{C}$ for Unit B₂ time, and $12.6\text{ }^{\circ}\text{C}$ for Unit B₃ and Unit D time. Because spring temperature is always equal to or higher than MAT for air in the area today, MAT must have been $\geq 10.8\text{ }^{\circ}\text{C}$ colder during Unit B₂ deposition than today at the sample sites, and $\geq 5.6\text{ }^{\circ}\text{C}$ colder during Unit B₃ and Unit D deposition.

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